Waste heat valorisation at multiple scales: focus on in-building waste water and regional heat recovery

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to my grandparents,
who introduced me to the world of physics
by showing me the infeasibility of a perpetuum mobile

to my parents and my sister,
who introduced me to the world of art

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Abstract

Environmental issues like climate change, resources depletion and the pollution of air, water and soil represent major challenges for the sustainable development of our society. Several of these issues are related to energy consumption, and energy efficient solutions must be proposed to address these. In that framework, this thesis focuses on waste heat valorisation by proposing methods for the data characterisation, assessment and optimisation of heat recovery at the building, city and regional scales.

As a first contribution, a method for the modelling of domestic hot water streams (shower, bath, washing up, etc.) in hotels, nursing homes and households at the building scale is presented. This method provides specific data on energy consumption and temperature level for each stream, taking into account the number of inhabitants and households, the end-use occurrence, as well as the use frequency and duration. The energy consumption can be put in relation to the total heating demand of the building and, by spatial allocation and bottom-up data aggregation, of a district, a city or a region. It is demonstrated in a case study that with the construction of near-zero energy buildings and the improvement of the thermal envelope of existing ones, domestic hot water will represent in the future between 30 and 50% of the residential building heating demand.

Considering these findings, measures to improve the energy efficiency related to domestic hot water use must be addressed. Residential waste water streams are therefore complementarily characterised, and energy consumption and investment cost calculations methods at the building level are presented. Different in-building waste water heat recovery configurations are then assessed using pinch analysis. The residential heating savings of shower and grey water heat recovery systems of a real case study range between 1 and 12%, while in high efficiency residential buildings savings between 6 and 22% are obtained. An integrated approach combining heat recovery, temperature optimisation and heat pump use leads to heating savings ranging between 28 and 41% in high efficiency single family and multifamily buildings, respectively, therefore demonstrating the relevance of such a holistic method.

Concerning regional waste heat valorisation, an integrated optimisation method, based on a mixed integer linear programming model and maximising profits for energy service companies, is proposed. The model takes into account the specific energy price of the heat sinks, the

distances between sources and potential users, the energy losses due to heat transportation as well as the related investment and operating costs. The model also includes the optimal selection of the backup heating technology. With the energy prices of 2015 and considering the Southern region of Luxembourg, the production of electricity proves to be viable for waste heat prices below 10 €/MWh, while waste heat could still be valorised for heating demand at prices up to 25 €/MWh. At that price, profits of more than 10 M€/a from the transport of waste heat and the electricity production of combined heat and power systems are obtained.

By proposing improved and novel methods related to the valorisation of waste heat at multiple scales, this thesis supports the development of energy efficiency solutions in and across the building, commercial and industrial sectors.

Key words: domestic hot and waste water characterisation, in-building waste water heat recovery, MILP-based regional waste heat valorisation, energy service companies.

Résumé

Les problèmes environnementaux comme le changement climatique, l'épuisement des ressources ainsi que la pollution des milieux naturels représentent des défis majeurs pour le développement durable de notre société. Plusieurs de ces impacts environnementaux sont liés à la consommation d'énergie et des solutions à haute performance énergétique doivent être développées pour les réduire. Dans ce cadre, cette thèse porte sur la valorisation de la chaleur excédentaire en proposant des méthodes de caractérisation de donnée, d'évaluation et d'optimisation de la récupération de chaleur à l'échelle du bâtiment, de la ville et de la région.

En premier lieu, une méthode de caractérisation des flux d'eau chaude sanitaire (douche, bain, etc.) dans les hôtels, les maisons de soins et les ménages à l'échelle du bâtiment est proposée. Cette méthode fournit des données spécifiques sur la consommation d'énergie en fonction du nombre d'habitants et des ménages, de la fréquence et de la durée d'utilisation. La consommation énergétique peut ainsi être mise en relation avec la demande totale de chauffage du bâtiment et, par localisation et agrégation des données, d'un quartier, d'une ville ou d'une région. Il est démontré qu'avec la construction de bâtiments à très faible consommation en énergie et l'amélioration de l'enveloppe thermique des immeubles existants, l'eau chaude sanitaire représentera à l'avenir entre 30 et 50% de la demande résidentiel en chauffage.

Compte tenu de ces résultats, il convient de prendre des mesures pour améliorer l'efficacité énergétique liée à l'eau chaude sanitaire. Les eaux usées résidentielles sont donc caractérisées de manière complémentaire et des méthodes de calcul de la consommation d'énergie et des coûts d'investissement sont proposées. Différentes configurations de récupération de chaleur des eaux usées sont évaluées à l'aide d'une analyse par pincement. Une approche intégrée combinant la récupération de chaleur, l'optimisation de la température et l'utilisation d'une pompe à chaleur conduit à des économies de chauffage entre 28 et 41% dans les bâtiments unifamiliaux et multifamiliaux à haute performance énergétique, démontrant ainsi la pertinence d'une telle méthode holistique.

En ce qui concerne la valorisation régionale de la chaleur résiduelle, une méthode d'optimisation intégrée maximisant les bénéfices, basée sur un modèle de programmation linéaire

en nombres entiers mixtes, est proposée pour les entreprises de services énergétiques. Le modèle prend en compte le prix de l'énergie spécifique des utilisateurs, les distances, les pertes de chaleur dues au transport, les coûts d'investissement et d'exploitation ainsi que la sélection optimale du système de chauffage de support. Considérant les prix de l'énergie de 2015 dans un cas d'étude réel, la production d'électricité s'avère viable pour les prix de chaleur excédentaire en dessous de 10 €/MWh, et cette chaleur pourrait encore être valorisée pour des besoins de chauffage jusqu'à un prix de 25 €/MWh. A ce prix, des bénéfices de plus de 10 M€/a sont obtenus par le transport de la chaleur et la production d'électricité des systèmes de cogénération.

En proposant des méthodes améliorées et novatrices liées à la valorisation de la chaleur excédentaire à des échelles multiples, cette thèse soutient le développement de solutions améliorant l'efficacité énergétique à travers les secteurs du bâtiment, du commerce et de l'industrie.

Mots clefs: caractérisation des flux d'eau chaude sanitaire et des eaux usées, récupération de chaleur sur les eaux usées dans les bâtiments, valorisation régionale de la chaleur excédentaire sur base d'une approche de programmation linéaire en nombres entiers mixtes, entreprises de services énergétiques.

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1 Introduction

1.1 Context

Climate change, natural resource depletion and anthropogenic pollution of air, water and soil represent major environmental challenges for our society. Following the United Nations Millennium Development Goals, 194 countries adopted the United Nations Sustainable Development Goals in 2015 addressing these challenges. Among the 17 Goals, one particularly focuses on the access to affordable, reliable, modern as well as sustainable energy, with the objective to double the improvement rate of energy efficiency by 2030 (United Nations [221]). The use of fossil fuels is particularly targeted by this objective, as their availability is limited, and their combustion is the source of pollutants, like SO_x and NO_x, leading to negative impacts on human health, flora and fauna (Bilgen [21]). Their consumption is also an important contributor to greenhouse gas emissions, the cause for climate change. In 2010, 25% of these greenhouse gas emissions were related to the indirect emissions related to electricity and heat production (Victor et al. [229]). Energy saving measures therefore address several of the United Nations Sustainable Development Goals simultaneously.

According to the U.S. Energy Information Administration [223], the global delivered energy, excluding electricity losses, amounted to 120 PWh in 2012, with the industrial sector making up 54% of this use, followed by the transport sector with 31%, the residential sector with 13% and the commercial sector with 7% (Fig. 1.1). The business-as-usual projection does not foresee major changes in this cross-sectoral distribution. However, the amount of delivered energy is expected to further increase by 44% until 2040 among all sectors, unless major energy efficient solutions are implemented.

In terms of energy use, liquid fuels represented 44% of the delivered energy in 2012, natural gas 20%, electricity 16%, coal 15% and renewable energies 5%. When excluding the transport sector, where the demand was covered almost 100% by liquid fuels (Fig. 1.2), the delivered energy was 26% as natural gas and liquid fuels , 22% as electricity, 20% as coal and 6% as renewable energies.
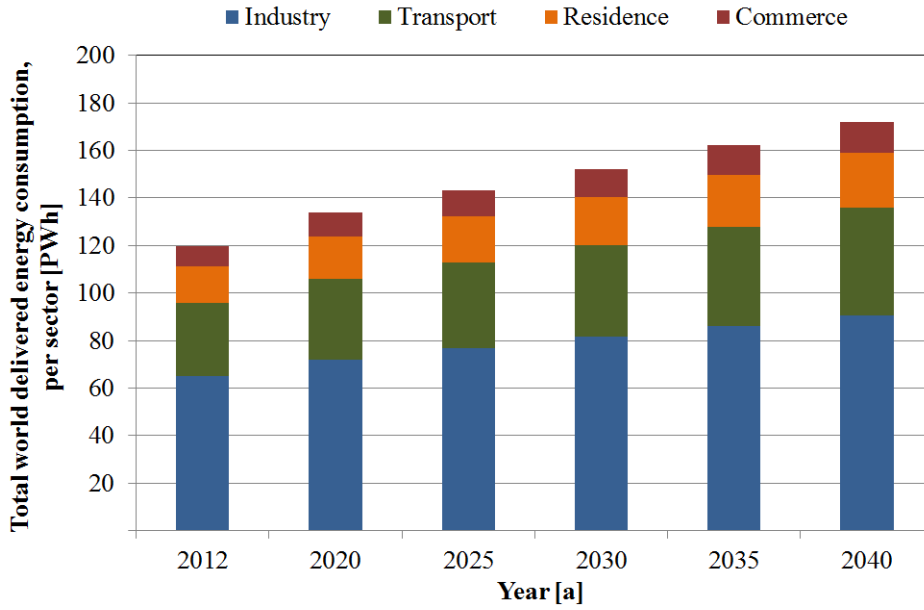
Figure 1.1: World delivered energy according to sector, excluding electricity losses (U.S. Energy Information Administration [223])
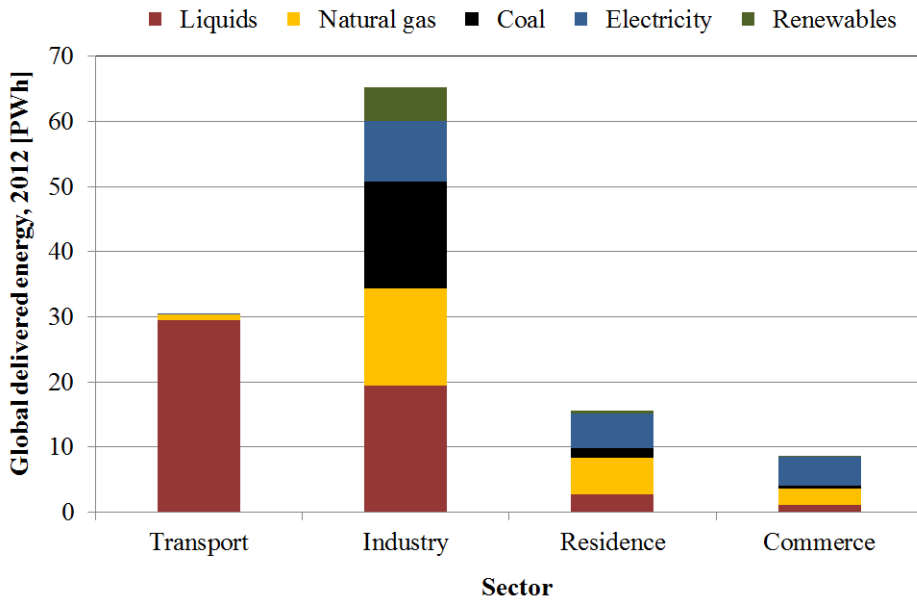
Figure 1.2: World delivered energy type according to sector in 2012 (U.S. Energy Information Administration [223])

One opportunity to improve energy efficiency in and across the residence, commerce, transport and industry sectors consists in the recovery of waste heat. Forman et al. [78] estimated the global, theoretical, waste heat potential in 2012 to reach 68 PWh, with 21% of this potential available at temperatures above 300°C, 16% between 300 and 100°C and 63% below 100°C (Fig.

1.3). The largest waste heat potential would be obtained from electricity production (44%), followed by transport (25%), industry (13%), residence (12%) and commerce (6%).
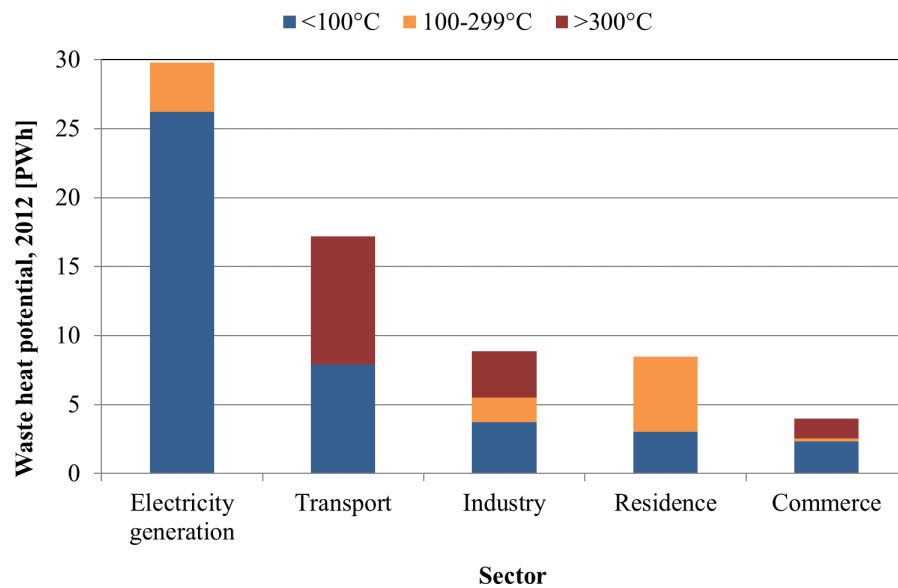
Figure 1.3: Waste heat potential according to sector (Forman et al. [78])

While these outcomes highlight an important potential for waste heat recovery, especially when only energy quantities are considered, its actual valorisation has so far been limited by technical, organisational and economic constraints (McKenna and Norman [136], Walsh and Thornley [235], Chew et al. [41], Brueckner et al. [33]). Financial barriers (high investment costs, high payback time, financial risks) are among the major hurdles to waste heat valorisation (Brückner et al. [30], Oluleye et al. [153], Broberg-Viklund [31]). Furthermore, the detection and selection of adequate heat sinks are often indicated as important constraints to the reuse of waste heat (Viklund and Johansson [231], Miró et al. [142], Oluleye et al. [154]).

Scientists have been addressing these financial and selection issues for over 40 years with the development of process integration methods (Klemeš [113]). Process integration consists of an holistic approach to the optimal combination of operations in a process or between several processes with the objective to decrease resource consumption and pollutant emissions (Varbanov [224]). These methods are generally based on pinch analysis (Linnhoff and Flower [122], Linnhoff et al. [124]), operations research formulations (Papoulias and Grossmann [159, 160, 161]) or a combination of the two approaches (Maréchal and Kalitventzeff [134]). While the initial focus of process integration methods was on industrial process and factory optimisation (e.g. Klemeš et al. [114], Varbanov et al. [226], Amon et al. [6]), the scope of process integration methods was enlarged to encompass industrial zones to further profit from waste heat transfer and utility sharing opportunities (e.g. Stijepovic and Linke [207], Hackl et al. [91], Stijepovic et al. [208]). Two further fields of application are still relatively new to process integration: urban waste water heat recovery (WWHR) and regional waste heat valorisation (RWHV).

Waste water heat recovery consists in the reuse of the heat contained in the waste water, either at the building level (in-building solution), or at the sewage level (Hepbasli et al. [96]). Considering that domestic hot water demand will represent up to 50% of the heating demand in high efficiency buildings (Frijns et al. [80]), WWHR is expected to become a relevant topic in the future. The valorised heat can be used either for hot water preheating or as a heat source for a heat pump to cover the total heat demand of the building. While the potential of in-sewer heat recovery has been addressed (Abdel-Aal et al. [1], Cipolla and Maglionico [43], Durrenmatt and Wanner [51]), the energy saving impact of in-building solutions has yet to be analysed in detail at a building or city level.

Concerning regional waste heat valorisation, this development is a further increase in scope of process integration methods. As waste heat can not always be valorised on-site or in the industrial zone due to the above-mentioned constraints, it may be recovered for other users. Persson and Werner [170] estimated that approximately 90% of the EU residential and service sectors heating demand could theoretically be covered by excess heat from manufacturing industries, power production and waste incineration. Regional waste heat valorisation opens the opportunity to create new energy services related to waste heat management, a subject that has been barely addressed from the point of view of energy service companies (ESCos).

While assessment and optimisation methods addressing waste water heat recovery and regional waste heat valorisation are applied at different scales, they share the necessity for high quality input data on building heat requirements. Heating demand characterisation has been addressed in the past, with a major focus on the modelling of space heating. However, domestic hot water (DHW) energy modelling, similar to what has already been done in the water field (Blokker et al. [22], Pieterse-Quirijns et al. [172]), has so far not been considered in detail.

This thesis therefore targets these three topics by proposing data characterisation, assessment and optimisation methods supporting the valorisation of waste heat at building, city and regional scale.

1.2 Scientific background

The scientific background covered in this thesis is presented below, while specific literature reviews are conducted in the respective Chapters 2, 3 and 4.

1.2.1 Domestic hot water streams characterisation

A large number of publications addressed the quantification and spatial allocation of heating in urban systems, as demonstrated in the reviews of Keirstead et al. [109], Allegrini et al. [3] and Reinhart and Davila [182]. The latter authors highlighted the fact that bottom-up urban system modelling will grow in importance due to their higher level of detail. This modelling

approach is often coupled to geographical information systems (GIS) data on building foot-print, height, occupant number etc., which can be used to characterise the building energy demand. Multiple linear regression analysis combined with GIS data was recurrently used for the calculation of the space heating demand (e.g. Mastrucci et al. [135], Schüler et al. [189], Nouvel et al. [150]). However, the reliability of data still needs to be improved to limit the level of uncertainty of the results (Reinhart and Davila [182]). In particular, a lack of methods to characterise in detail the energy demand of specific domestic hot water streams (showering, bathing, washing up, etc.) is observed.

Domestic hot water energy demand in buildings has usually been calculated as a function of the building surface and considered as a single stream (Girardin et al. [85], Jennings et al. [106], Fonseca and Schlueter [77], Nouvel et al. [150]). This approach, while reflecting the centralised hot water production at the heating utility level, fails to acknowledge that hot water demand depends on the end-use occurrence and occupant number (Blokker et al. [22]). Also, DHW streams have different temperature level requirements (Yao and Steemers [242], Schramek [192]), that can influence the heating system design, in particular when low temperature floor heating is involved (Hesaraki et al. [97]). A more specific bottom-up approach to DHW characterisation is therefore necessary to better quantify the energy demand at building and urban scale, thus improving the outcomes of regional waste heat valorisation methods. Also, the energy consumption of the various DHW streams relative to space heating has not been specifically quantified yet, an obvious hurdle for the assessment of the relevance of WWHR systems as energy efficiency measure in the residential sector.

1.2.2   In-building waste water heat recovery

In the field of in-building WWHR, several works focused on horizontal and vertical shower heat exchangers (e.g. Meggers and Leibundgut [138], Kordana et al. [117], Torras et al. [217]), also in combination with heat pumps and/or solar energy (Chen et al. [39], Dong et al. [49], Tanha et al. [212]). Other authors analysed waste water collecting and recovery systems as to their energy and economic savings (Hepbasli et al. [96], Postrioti et al. [176]). The assessment methods were based either on experimental setups (Wong et al. [240], Dong et al. [49], Torras et al. [217], Postrioti et al. [176]), simulation (Liu et al. [125], Chen et al. [39], Torras et al. [217]) or exergy calculations (Meggers and Leibundgut [138]). As waste water energy data is still very scarce (Meggers and Leibundgut [138]), a few authors proposed various waste water models, e.g. for showers (Guo et al. [89], Dong et al. [49]) or dishwashers (Persson and Werner [170], Bengtsson et al. [14]). Ni et al. [148] proposed a method to derive grey water temperatures as a function of hot and fresh water temperatures, without, however, providing further information on temperature loss coefficients used in their approach.

No detailed stream characterising methods considering inhabitant and household numbers at the building scale have been proposed so far. Furthermore, as past assessments focused particularly on the heating system, the energy savings were usually related to the energy

demand of DHW. These savings were thus not put in relation to the building type (which constrains the actual implementation of such solution - McNabola and Shields [137]) or the total heating demand and therefore its energy efficiency. Furthermore, the energy saving impact of such solutions have barely been considered at large scale. The few publications addressing this topic only used a simplified top-down approach, considering a fixed energy saving ratio per building to quantify the impact of WWHR at the level of a district, a city or a region (Leidl and Lubitz [118], Ni et al. [148], Deng et al. [46]). The specific quantification of energy savings based on a bottom-up approach has yet to be proposed.

1.2.3 Regional waste heat valorisation

By better characterising the energy demand for domestic hot water, and therefore of urban systems, the outcomes of RWHV assessments are also improved. The valorisation of industrial waste heat at a regional scale has been addressed by Perry et al. [166] in the framework of their locally integrated energy sector approach. The concept of a locally integrated energy sector is based on total site heat integration (Dhole and Linnhoff [48], Klemeš et al. [114]), which targets maximal energy savings of industrial processes by process integration. According to the review of Liew et al. [119], the methodological developments on locally integrated energy sector approaches mostly focused on the inclusion of the aspect of demand variability, e.g. with the multi-period approach of Nemet et al. [145]. Waste heat valorisation at large scale has been considered particularly for urban systems, with the works of e.g. Tveit et al. [219], Fang et al. [71], Xia et al. [241]. The economic profitability of such concepts was also recurrently addressed, with the objective function often being the minimisation of investment and operating costs of the heat user (Svensson et al. [210], Oh et al. [152], Eriksson et al. [57], Sandvall et al. [188], Sameti and Haghighat [186]). Concerning the actual implementation of such concepts, Ammar et al. [5], Brueckner et al. [33] and Päivärinne and Lindahl [173] highlighted the reluctance of industries (both as heat source and sink) and municipalities alike to actually engage in the planning, investment and management tasks of RWHV projects, as these are not part of their core activities. The inclusion of an energy service company (ESCo) as third actor fulfilling these tasks is therefore necessary to implement waste heat valorisation at the regional scale.

However, specific RWHV optimisation methods for energy service companies have, so far, not been formulated. While the minimisation of costs are very relevant aspects to such an approach, the key issue is profitability (Deng et al. [45]). These profits depend also on the optimal selection of the most appropriate heat sinks, which is influenced by the sink initial energy price, an aspect, with the exception of Oluleye et al. [153], so far not taken into account. Furthermore, as heat supply must be guaranteed in case of waste heat supply failure, a backup heating system must also be included in the system design. The selection of the optimal technology would further maximise the profits and therefore improve even more the service value of the ESCo (Brady et al. [28]).

1.3 Objectives

Considering the above-mentioned shortcomings, the objective of this thesis is threefold:

1. Propose a characterisation method for domestic hot water and waste water streams as a function of specific building characteristics, e.g. occupant number, end-use occurrence, use duration and frequency.

2. Develop a method to assess in detail the relevance, in terms of energy savings and costs, of various waste water heat recovery systems in buildings and, by data aggregation, at the level of a city or a region.

3. Formulate an ESCo-specific optimisation model for the valorisation of waste heat at a regional scale and for the selection of a heating technology used as backup system.

By characterising DHW according to their temperature levels, thermal loads, end-use occurrence as well as inhabitant and household numbers, the quantification of the energy demand of buildings and of urban systems is improved. With the description of the related waste water streams complementary to the DHW modelling approach, the opportunity to assess in detail in-building WWHR systems at the building, city and regional level is taken. Finally, a novel, integrated, optimisation method on regional waste heat valorisation specifically formulated for energy service companies is proposed.

1.4 Outlines

The first development of this thesis consists in the characterisation of domestic hot water streams (Chapter 2). The methodology first covers the equations necessary to determine the energy consumption of the various DHW streams (Section 2.2). A review of typical European values for mass flows, temperature levels, occurrence rate, etc. as inputs to these equations is then conducted. The characterisation method is demonstrated in a real case study applied to the city of Esch-sur-Alzette (Grand-Duchy of Luxembourg - section 2.3). The resulting outcomes are compared with literature values. The relevance of the various DHW stream energy consumption as a function of the building age and thus its thermal efficiency is presented. In addition, the impact of an integrated approach combining the use of a heat pump and hot water temperature reduction in a low energy building is demonstrated. The final section sees the advantages and shortcomings of the proposed method discussed (Section 2.4).

Waste water stream characterisation and their valorisation at the building and city scale are addressed in Chapter 3. Based on the method and data described in the preceding chapter, the waste water streams are characterised as to their drain temperature (Section 3.2). Methods for the calculation of the investment costs and the energy savings using pinch analysis are proposed in the same section. Furthermore, various shower and grey water heat recovery

configurations are assessed as to their energy savings. Two case studies are then presented (Section 3.3). First, the impact of the implementation of a horizontal shower heat exchanger and a grey water heat recovery system in the residential buildings of Esch-sur-Alzette is assessed. In the second case study, low energy and high efficiency single family and multifamily buildings are considered for the application of the same technologies as well as for an integrated approach combining hot water temperature reduction, heat recovery and the use of a heat pump. The proposed approach is then discussed as to its strengths and disadvantages (Section 3.4).

A regional waste heat and utility optimisation approach for energy service companies is described in Chapter 4. Following the literature review, the multi-period, mixed integer linear programming model is presented (Section 4.2). The economic constraints are formulated to calculate the profits generated from the revenues of waste heat supply and electricity production, taking into account operating costs related to energy consumption as well as annualised investment costs linked to the acquisition of the heat exchangers, pipes and backup heating systems. The energy constraints are based on the heat cascade formulation, adapted to consider heat losses from transportation. The method is demonstrated in a case study set in the Southern region of Luxembourg, with two steel plants as heat sources as well as three factories and nine towns as heat sinks (Section 4.3). The method is first deployed using various waste heat prices at the sources. In a second step, the optimisation outcomes, considering a waste heat price generating the highest revenues for the steel plants, are presented in detail. The chapter closes with a discussion on the methodology (Section 4.4).

In Chapter 5, conclusions as to the proposed methodological developments and outcomes of the case studies are drawn. This thesis closes with some perspectives as to future developments.

2 Domestic hot water characterisation

This chapter is the updated postprint version of an article published in Applied Energy (Bertrand et al. [19]). A preliminary version was presented at the Biennial International Workshop Advances in Energy Studies (BIWAES) 2015 in Stockholm (Bertrand et al. [15]). This work was elaborated by the author of this thesis, in collaboration with François Maréchal and Nils Schüler from the Ecole Polytechnique Fédérale de Lausanne (Switzerland) as well as Riad Aggoune and Alessio Mastrucci from the Luxembourg Institute of Science and Technology (Luxembourg). The latter co-author contributed the section on total heat demand calculation using regression analysis (Section 2.3.1.2). The outcomes of the case study will be used by the national institute of statistics and economic studies of Luxembourg (Statec) in its reporting to the EU concerning the energy consumption of households, as required by the regulation on energy statistics (European Parliament [61], Eurostat [64]).

Abbreviations and symbols

Abbreviations

COP	coefficient of performance
DH	district heating
DHW	domestic hot water
GIS	geographical information system
MFB	multi family building
MUB	mixed-use building
OLS	ordinary least squares
SFB	single family building
SH	space heating

Symbols

b	specific bed number per room [room^{-1}]
c_p	heat capacity [kJ/kg*K]
d	use duration [s]
f	use frequency [capita*day]$^{-1}$, [household*day]$^{-1}$
m	room occupancy [%]
p	bed place occupancy [%]
$\dot{Q}$	thermal load [kW]
Q	energy [kWh]
R^2	coefficient of determination [-]
r	room number r [-]
S_n	DHW simultaneity factor [-]
s	stay duration [day]
T	temperature [°C]
t	time t [h]
$\dot{V}$	volumetric flow [m^3/s]
x_{floor}	useful floor surface [m^2]
x_{occ}	number of occupants [occupants]

Symbols

x_{type}	building type [-]
$x_{period,a}$	construction period a of buildings
y	dwelling energy consumption [kWh/a]
ε	random error term [-]
$\eta_{utility}$	utility efficiency [-]
ρ	density [kg/m^3]
σ	end-use occurrence [%]
υ	random value for end-use spatial allocation [-]

Subscripts

b	building b
e	end-use e
h	household h
o	occupant o
t	time t
u	unit u

2.1 Introduction

Cities are responsible for 75 % of the global energy consumption, as well as between 50 to 60% of the green house gas emissions (UN Habitat [220]) and therefore play a central role in the global improvement of energy efficiency. In that sense, new buildings shall be designed in the EU to be near-zero energy until 2020 (European Parliament [62]). In 2013, space heating (SH) household final energy consumption amounted to 2.33 PWh, while domestic hot water (DHW) reached 0.44 PWh - representing 16% of the total heat requirements - in the EU28 (Enerdata [54]). However, with improved thermal insulation, the relevance of DHW consumption is increasing. In the Netherlands, 23% of the household gas consumption is already related to DHW use, and new buildings see this contribution reach 50% of the energy consumption (Frijns et al. [80]).

So far, integrated urban energy assessments and optimisation mostly focused on the characterisation of space heating, and did not differentiate between the various DHW end-uses like

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showering, dish washing, etc. (Jennings et al. [106], Fonseca and Schlueter [77], Nouvel et al. [150]). Nevertheless, such a differentiation is conducted by Yao and Steemers [242], although relevant streams (shower and bath) are still aggregated as one stream, and by Aydinalp et al. [8], Widen et al. [239], Beal et al. [9], where the specific temperature levels of the various end-uses are not considered specifically. However, the differentiation and characterisation of DHW streams is of importance for an integrated approach to urban energy assessment and optimisation. With the distinction of the multiple domestic hot water end-uses, various energy saving measures can be more specifically addressed in an integrated way at urban scale (building blocks, streets, districts, city). In particular, various grey water heat recovery configurations, as described by Schmid [190], McNabola and Shields [137], Dong et al. [49] for buildings or by Abdel-Aal et al. [1], Elias-Maxil et al. [52], Hepbasli et al. [96] for sewer systems, requires the characterisation of the specific DHW streams. The characterisation of the various end-use temperatures also improves the assessment of the heating utility temperature level of buildings with low temperature space heating systems, as this level is determined by the DHW demand (Brand et al. [29]). So far, the hot water temperature level has generally been assumed at 60°C (Perry et al. [166], Girardin et al. [85], Kordana et al. [117]), but with more specific DHW streams, this level can actually be lowered. This again influences the selection of the optimal utility configuration, where heat pumps and low temperature waste heat recovery can become more competitive compared to biomass of fossil fuels. Finally, urban energy integration focusing on the optimisation of district heating (DH) systems only considered buildings equipped with hot water storage system (Weber [237], Fazlollahi [72], Elmegaard et al. [53]), although Thorsen and Kristjansson [214], Christiansen et al. [42], Rosa et al. [184] showed that a configuration without storage (stand-alone heat exchanger) can be equivalent or even better in terms of costs and energy efficiency. The modelling of such a configuration, however, requires the characterisation of the DHW loads according to the main end-uses.

Considering the above-mentioned shortcomings, the objective of this work is to propose a detailed urban DHW characterisation method differentiating between the various end-uses encountered in domestic buildings (households) and lodgings (hotels and nursing homes), and describing them as to their temperature levels. The input data as well as the outcomes are geoallocated to benefit from the spatial differentiation, which allows the detection of locations with specific energy consumption, the aggregation and representation of the data according to building blocks, streets or districts as well as the planning of centralised energy utilities like district heating system.The proposed method can therefore be applied, when the required data (inhabitant and household numbers, building type, etc.) is available, at the level of cities, districts, streets and building blocks. Based on these DHW models, a complementary method to calculate the load of DH stand-alone heat exchangers is formulated.

The main contributions of the proposed method are therefore to increase the detail level of urban thermal energy assessments, as well as to improve integrated urban energy optimisation with the consideration of DHW temperature for optimal heating utility type selection and an additional district heating system configuration.

To this end, the methodology to characterise the energy demand and load requirement of various DHW end-uses is presented in Section 2.2. The equations for households, hotels and nursing homes are developed, and a review on European domestic water use is conducted. In Section 2.3, the proposed characterisation method is applied to the households, hotels and nursing homes of the city of Esch-sur-Alzette (Grand-Duchy of Luxembourg), where the DHW energy demands are calculated and compared to calculated or measured values mentioned in scientific publications and technical literature addressing DHW demand. The energy use of the various DHW streams are also put in relation to the total and space heating energy demand in this case study. Temperature level and utility load requirements as well as the impact of the proposed DHW characterisation on the energy integration of heat pumps are finally addressed in this section. Considering the outcomes of the case study, Section 2.4 covers the advantages, shortcomings and main contributions of the proposed method.

2.2 Method

This section describes the proposed method for urban DHW characterisation. In Section 2.2.1, equations for the DHW-related energy consumption as a function of occupant and units numbers (e.g. a household in multifamily buildings, a room in a hotel), space heating energy demand as well as the utility load of stand-alone heat exchangers are developed. A review of European literature on the characterisation of domestic water use, considering typical flows, use frequency and duration, temperature and occurrence is conducted in Section 2.2.2. The spatial allocation of the various DHW end-uses according to inhabitant and household numbers, allowing the spatial differentiation of the results, is also presented in that section.

2.2.1 Characterisation methodology

2.2.1.1 DHW end-use load

The thermal power requirement $\dot{Q}_e$ of a DHW end-use e is calculated considering its density ρ, its heat capacity c_p, the water volumetric flow $\dot{V}_e$ and the difference between hot and fresh water temperatures ($T_e - T^{fresh}$) (Eq. 2.1). Both volumetric flow and hot water temperature are specific to the considered end-use e.

$$\dot{Q}_e = \rho \times c_p \times \dot{V}_e \times (T_e - T^{fresh}) \tag{2.1}$$

2.2.1.2 DHW and space heating energy demand

Domestic buildings   The daily energy demand Q_e^{DHW} of a DHW end-use e is the product of the thermal power $\dot{Q}_e^{DHW}$ with its use duration d_e (when necessary, corrected to the appropriate time unit) and daily use frequency f_e (Eq. 2.2).

$$Q_e^{DHW} = \dot{Q}_e^{DHW} \times d_e \times f_e \tag{2.2}$$

In a household, some of the DHW end-uses e are related to the activities of the occupant o (e.g. showering, bathing, washing and shaving), while other streams (e.g. dish washing) are directly linked to the household h. The total DHW-related yearly energy demand of the household $Q^{DHW,household}$, expressed in kWh/a, is therefore obtained by summing the daily energy consumption $Q_{e,o,t}^{DHW}$ of the various DHW streams e of occupant o for time t, with the energy use $Q_{e,h,t}^{DHW}$ required at household level h for time t (Eq. 2.3).

$$Q^{DHW,household} = \sum_{t=1}^{365} \left(\sum_e Q_{e,h,t}^{DHW} + \sum_o \sum_e Q_{e,o,t}^{DHW} \right) \tag{2.3}$$

For multifamily buildings, some DHW end-uses (e.g. cleaning of common spaces) are required at building b level. The yearly DHW energy demand $Q^{DHW,building}$ of a building is therefore obtained by summing up the DHW energy demand $Q_{e,o,h,b,t}^{DHW}$ of the occupants, $Q_{e,h,b,t}^{DHW}$ of the households and $Q_{e,b,t}^{DHW}$ of the streams attributed to the building common areas over 365 days (Eq. 2.4).

$$Q^{DHW,building} = \sum_{t=1}^{365} \left[\sum_e Q_{e,b,t}^{DHW} + \sum_h \left(\sum_e Q_{e,h,b,t}^{DHW} + \sum_o \sum_e Q_{e,o,h,b,t}^{DHW} \right) \right] \tag{2.4}$$

Lodgings While the equations above can also be applied to hotels and nursing homes (the room replacing the household), the necessary input data are scarce. An alternative to Eq. 2.4 can be used, considering several parameters related to room and bed occupancies:

- the total room number r,

- the yearly room occupancy m, expressed in percentage,

- the average bed number per room β,

- the yearly bed place occupancy p, expressed in percentage.

Using Eq. 2.5, the energy demand of the various end-uses e related to the occupant $\sum_e Q_e^{DHW,occupant}$, room $\sum_e Q_e^{DHW,room}$ and building $\sum_e Q_e^{DHW,building}$ are summed up according to the number of occupants (product of bed number per room and bed place occupancy) and the number of occupied rooms (product of number of rooms and room occupancy) for the whole year.

$$
\begin{aligned}
Q^{DHW,lodging} \quad = \quad & 365 \times [\sum_e Q_e^{DHW,building} + \\
& r \times \left(m \times \sum_e Q_e^{DHW,room} + \beta \times p \times \sum_e Q_e^{DHW,occupant} \right)]
\end{aligned}
\qquad (2.5)
$$

Space heating energy demand   With the characterisation of the DHW energy consumption, the space heating energy consumption is calculated considering the total fuel consumption and the efficiency of the heating utility $\eta_{utility}$ (Eq. 2.6).

$$
Q^{SH,building} = \left(Q^{total} \times \eta_{utility} \right) - Q^{DHW,building}
\qquad (2.6)
$$

In case measured data are not available, the total heat consumption can be conveniently determined using multiple regression analysis out of a sample of measured consumption data. Multiple linear regression is one of the different techniques available to predict the energy consumption of buildings based on measured consumption data as well as several other independent variables, instead of only one as with simple linear regression. This technique is commonly used by other authors in literature for similar studies (Wahlstrom and Harsman [233], Schüler et al. [189]). Guerra Santin et al. [88] highlighted that building characteristics determine a large part of the energy use in dwellings. Howard et al. [101] used the total floor area of each included building type as a predictor of fuel consumption. Mastrucci et al. [135] used floor surface, and the combination of type of dwelling and period of construction to predict the natural gas consumption of residential buildings. Compared to other techniques, linear regression is particularly promising for this goal due to reasonable accuracy and relatively simple implementation (Fumo and Biswas [83]).

2.2.1.3   Utility load calculation

Utility with thermal storage   The large majority of heating utilities in buildings cover both domestic hot water and space heating demands (Schramek [192])), and are usually used in combination with a hot water storage system. With the space heating energy consumption and data on outdoor temperature, the space heating load requirements can be obtained using the heating signature method (Girardin et al. [85]). The decentralised utility load (Eq. 2.7) is obtained by summing the maximal space heating load $\dot{Q}_{max}^{SH}$ and the continuous, averaged over 8'760 hours, DHW load (Schramek [192], Girardin et al. [85]). It is referred to the work of Becker and Maréchal [12], Fazlollahi et al. [73, 75] for the optimised design of thermal storage tanks.

$$
\dot{Q}^{utility,w.storage} = \dot{Q}_{max}^{SH} + \frac{Q^{DHW,building}}{8760}
\qquad (2.7)
$$

Utility without hot water storage   Buildings connected to a district heating network are not necessarily equipped with a local DHW storage system (Christiansen et al. [42], Rosa et al. [184], Tol and Svendsen [215]). In literature, several methods to design the heat exchanger (HE) are proposed: while Gaderer [84], Tol and Svendsen [215] add up both SH and DHW load, Rosa et al. [184] considers only DHW, and Thorsen and Kristjansson [214] proposes to design the HE according to the highest load between DHW and SH. Considering building thermal inertia and the short DHW pulse duration, the approach of Thorsen and Kristjansson [214] is used for this work (Eq. 2.8).

$$\dot{Q}^{utility,no\ storage} = \begin{cases} \dot{Q}^{utility,DHW} & if\ \dot{Q}^{utility,SH} < \dot{Q}^{utility,DHW} \\ \dot{Q}^{utility,SH} & if\ \dot{Q}^{utility,SH} > \dot{Q}^{utility,DHW} \end{cases} \tag{2.8}$$

To determine the DHW power requirements of one household, the load of the DHW end-use with the highest value is selected and multiplied by a simultaneity factor $S =1.15$ (Schramek [192]). It is considered that the various large end-uses (e.g. bathtub, dish washing and showering in households) are available once and are not used simultaneously, but that smaller end-uses can be required at the same time than a large DHW appliance (Eq. 2.9).

$$\dot{Q}^{DHW,household} = 1.15 \times \dot{Q}_{max}^{DHW} \tag{2.9}$$

For multifamily buildings, mixed-use buildings and lodgings, the DHW thermal power requirement at building level is not obtained by summing up the loads of the single end-uses of the u units, as not all hot water demands occur at the same time (Thorsen and Kristjansson [214], Schramek [192]). Instead, in order to avoid an over-sizing of the utility, and thus higher investment costs, a simultaneity factor S_u is considered, which is multiplied by the sum of the single largest hot water end-use $\dot{Q}_{u,max}^{unit}$ of each unit u (Eq. 2.10).

$$\dot{Q}^{DHW,building} = S_u \times \sum_u \dot{Q}_{u,max}^{unit} \tag{2.10}$$

The simultaneity factor S_u is determined according to the number of units u in the building. S_u values are based on empirical data, and several models have been proposed to describe its behaviour (see Gaderer [84] and Christiansen et al. [42] for comparisons of simultaneity factor models). The simultaneity factors S_u using the equations provided by Thorsen and Kristjansson [214] and Gaderer [84] are represented in Fig. 2.1.

Considering that the equation of Thorsen and Kristjansson [214] has been specifically designed for Danish hot water utility design conditions (32.3 kW) and that the results are still overestimated when compared to measured data (Thorsen and Kristjansson [214], Christiansen et al. [42]), the equation of Gaderer [84] is selected (Eq. 2.11).
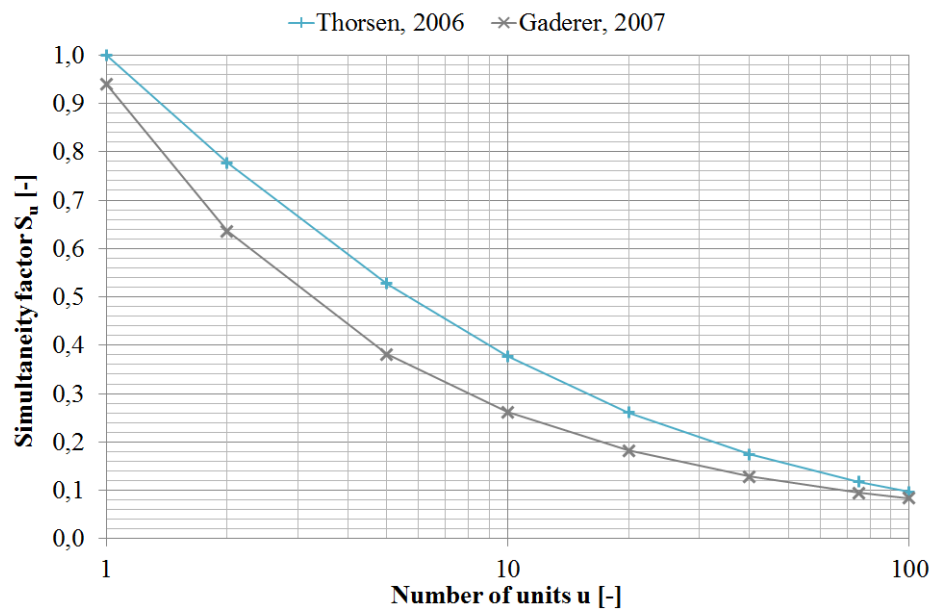
Figure 2.1: Simultaneity factors (Thorsen and Kristjansson [214], Gaderer [84])

$$S_u = 0.02 + 0.92 u^{(-0.58)} \tag{2.11}$$

2.2.2 Input data

In order to apply the proposed method, the following input data are required:

- End-use temperature,

- Volumetric flow for load calculation,

- Use frequency and duration,

- Geographical allocation of end-uses, occupants and unit numbers.

2.2.2.1 Temperatures

The inlet temperature of fresh water T_{in}^{fresh} varies over the seasons between 5°C and 15°C, but is, for yearly assessments, generally assumed at 10°C (Spur et al. [197], Widen et al. [239]). End-use temperature data are generally scarce. Yao and Steemers [242] and Schramek [192] give identical end-use temperatures for bath and shower, hand washing and hand dish washing (Tab. 2.1), while Wong et al. [240] mentions an average temperature of 40.9°C for showers.

Table 2.1: DHW end-use temperatures (Yao and Steemers [242], Schramek [192])

End-use type [-]	Temperature [°C]
Hand washing	35
Washing and shaving	35
Hand dish washing	55
Showering	40
Bath filling	40

2.2.2.2 Volumetric flows

Volumetric flow data for European DHW end-uses are summarised for domestic and lodging buildings in Tab. 2.2 and Tab. 2.3, respectively. Widen et al. [239] provides water consumption of 25 different DHW streams, of which three, indicated in Tab. 2.2, have a particularly high energy consumption. For non-European data, it is referred to DeOreo et al. [47], Hendron and Burch [95], Neunteufel et al. [147], Beal et al. [10], Cahill et al. [37], Kenway et al. [110], Rathnayaka et al. [181], Makki et al. [132].

Concerning household DHW streams, a value around 0.13-0.14 l/s for showers appears to be common. For bathtubs, the volumetric flow depends of the considered volume. The volumetric flow of kitchen sinks revolves around 0.1 l/s, although lower and higher values are reported. Bathroom sink volumetric flow data show the largest variance, with values between 0.03 and 0.1 l/s.

2.2.2.3 Use duration and frequency

While data on volumetric flow of DHW are available in the literature, European data on use frequency and duration (Tab. 2.4 and Tab. 2.5, respectively) are scarce. Blokker et al. [22] mentions a total kitchen tap use frequency of 12.6 (household day)$^{-1}$, which is subdivided between hand washing and hand dish washing at one fourth each, according to the penetration rate mentioned in the publication (the remaining 50% water use is for drinking, cooking, etc.). The tap use frequency of Neunteufel et al. [147] is distributed evenly between kitchen and bathroom sinks. Data on bathtub and shower use frequencies in non-European countries are given by Hokoi et al. [100], Kenway et al. [110].

2.2.2.4 Streams occurrence and spatial allocation

The occurrence of a dish washing machine or a bathtub in a household or a room is not automatically given (Blokker et al. [22]). As DHW end-use occurrence data are unlikely to be available at building level when conducting an urban energy assessment, it is proposed

Table 2.2: Domestic DHW volumetric flows, in l/s

Reference	Koiv and Toode [115]	Thorsen and Kristjansson [214]	Schramek [192]	Widen et al. [239]	Blokker et al. [22]	Neunteufel et al. [147]	Neunteufel et al. [147]	Gutierrez-Escolar et al. [90]
Pub. year	2006	2006	2007	2009	2010	2012	2012	2014
Country	Estonia	Denmark	Germany	Sweden	Netherlands	Austria	EU	Spain
Bathroom sink	-	-	0.05 / 0.083 [a]	-	0.04 [f]	0.03	-	0.07 * , 0.1
Kitchen sink	0.2	0.10	0.10 / 0.17 [b]	39 l [d]	0.08 / 0.13 [g]	0.03	-	0.10 * , 0.13
Shower	0.2	0.14	0.14	0.13 / 0.20 / 0.58 [e]	0.12 * , 0.14	0.13	0.13	0.17 * , 0.25
Bathtub	0.3	0.21	0.11 / 0.17 / 0.21 [c]	100 l/bath	0.20 [h]	76 l/bath	150 l/bath	250 l/bath

[a] small / large sink, [b] single / double sink, [c] size: 100 / 160 / 180, [d] dish washing, mix of tub and running water, [e] assumed value / modern tap / trad. tap, [f] washing and shaving, [g] hand washing / dish washing, [h] capacity: 120 l, * water-saving end-use

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Table 2.3: Lodging DHW volumetric flows, in l/s

Reference	Cobacho et al. [44]	Blokker et al. [23]
Pub. year	2005	2011
Country	Spain	Netherlands
Building type	Hotel	Hotel, nursing home,
Bathroom sink	15.26 l/day*guest	0.08 [a]
Showering	13.03 l/day*guest	0.12 / 0.14 / 0.37 [b]
Bath filling	-	0.20 [c]

[a]hand washing, washing and shaving,[b]water-saving/normal/comfort,[c]capacity: 120 l

Table 2.4: DHW use frequencies, in capita*day^{-1}

Reference	Cobacho et al. [44]	Blokker et al. [22]	Blokker et al. [23]	Neunteufel et al. [147]	Neunteufel et al. [147] (EU)
Building type	Hotel	Household	Offices, hotel, nursing home, restaurant	Household	Household
Bathroom sink	5.36 /day*guest	1.35 [a]	4.50 / 1.98 [c]	11.50	-
Kitchen sink	-	3.150 [b]	-	11.50	-
Showering	0.45 /day*guest	0.70	0.20 /0.80 [d]	0.70	0.8
Bath filling	-	0.04	0.20 [e]	0.03	0.1

[a]washing and shaving,[b]hand and dish washing, per household,[c]hand washing / washing and shaving,
[d]nursing homes / hotels,[e]capacity: 120 l

to distribute the occurrence according to the socio-economic level of the household or the district, depending of the data available. Geographically Weighted Regression would strongly support the spatial allocation, as it allows the disaggregation of the occurrence into the specific spatial unit while considering socio-economic predictors. However, this approach requires data as to the occurrence of the end-uses according to the socio-economic level, as well as the spatial distribution of the various levels, which is not always given locally. As simplified alternative, the end-use occurrences can be randomly distributed geographically as a function of the appliance occurrences o_e and by attributing random values ε_e between 0 and 1 to each end-uses in the household, e.g. using the RANDOM function in PostgreSQL [175]. The end-use is considered installed for $\varepsilon_e < o_e$ (Eq. 2.12).

Table 2.5: DHW use durations, in s

Reference	Cobacho et al. [44]	Schramek [192]	Blokker et al. [22]	Blokker et al. [23]	Neunteufel et al. [147]	Neunteufel et al. [147] (EU)
Building type	Hotel	Household	Household	Hotel, nursing home	Household	Household
Bathroom sink	-	90 / 120 [a]	40 [c]	16 / 40 [e]	59	-
Kitchen sink	-	300	15 / 48 [d]	-	59	-
Showering	270	360	510	510	288	474
Bath filling	-	900 / 1200 [b]	600	600	-	-

[a]small / large sink,[b]size: 100 & 160 / 180,[c]washing and shaving,[d]hand and dish washing, [e]hand washing / washing and shaving

$$\dot{Q}_e^{DHW} = \begin{cases} \dot{Q}_e & if \ \varepsilon_e < o_e \\ 0 & if \ \varepsilon_e > o_e \end{cases} \tag{2.12}$$

Values on the occurrence of dishwasher $o_{dishwasher}$ in households can be obtained from the respective national statistic agency (Tab. 2.6). Hand dish washing DHW demand is excluded for households equipped with a dishwasher.

Table 2.6: Dishwasher occurrence rates

Country	Occurrence [%]	Year of survey [year]	Source [-]
Austria	74	2012	Statistik Austria [205]
France	56	2014	INSEE [104]
Germany	68	2011	Statistisches Bundesamt [206]
Luxembourg	79	2011	Statec [200]
Switzerland	85	2014	Morgenthaler et al. [144]

Concerning the occurrence o_{bath} of household bathtubs, data is rare. 97.5% of the EU27 households in 2013 were equipped with a shower or a bathtub (Eurostat [65]) but a further breakdown between these two end-uses is almost non-existing in European and national household or production statistics. The French national statistic agency indicates that 74.4 % of the households were equipped with a bathtub in 2006, and 24.0% with only a shower

(INSEE [103]). A study on the water consumption in Austrian households showed that at least 25% of the 24 assessed households only used a shower (Neunteufel et al. [147]). Blokker et al. [22] indicate a dissemination rate of 36% for household bathtubs in the Netherlands. A survey conducted in China showed that between 20 to 100% of the households in Nanjing and around 70% of the Hefei households were only equipped with a shower (Hokoi et al. [100]).

Information on DHW appliance of non-residential buildings are also very scarce (Pieterse-Quirijns et al. [171], Blokker et al. [24]). Data on lodging bathtubs availability can be obtained from the site manager, from the site homepage or reservation service homepage. While Pieterse-Quirijns et al. [171] considers both showers and bathtubs available in Dutch hotel rooms, the number of hotel bathtubs in the USA has strongly decreased with newer constructions. In 2001, 95% of the Holiday Inn hotels were equipped with bathtubs, but hotels have recently been built either without (Indigo hotel) or only with a much smaller ratio varying between 25% (Marriott) to 55% (Holiday Inn) (Jones [108]).

2.2.2.5 Occupant and unit spatial allocations

Inhabitant and household numbers can be obtained from the municipality, preferably as a Geographical Information System (GIS) data set or as a table including the address of the building. While the spatial allocation is not strictly necessary for the proposed assessment at city scale, it allows a spatial differentiation of the DHW characterisation data, e.g. useful for the planning of district heating systems, or to present the outcomes at the level of building blocks, streets , districts, etc.

For lodgings, the best option to obtain the required data is to contact the facility manager, a solution which is nevertheless time-consuming and yields only a limited number of returns (Neunteufel et al. [147]). Should the detailed data not be available, public sources and statistical averages can be used to estimate the energy consumption. For hotels, national or regional tourism offices as well as reservation service homepage can provide the number of rooms r (e.g. Vienna Tourist Board [230], ONT [156], Switzerland Tourism [211]). Eurostat provides national and regional data on bedroom and bed place numbers, so that a specific bed number per room β (Eurostat [67]) as well as the net bed places occupancy p (Eurostat [66]) are available. Nursing home room and bed numbers can be obtained from dedicated internet sites (e.g. Bundesministerium fur Arbeit, Soziales und Kosumentenschutz [36], Capgeris [38], Privatinstitut für Transparenz im Gesundheitswesen GmbH [177], Haederli et al. [92], Luxsenior [130]). Occupancy rate in Europe is very high, with values in Luxembourg, Italy and France reaching 95.4% (Statec [201]), 93 - 98% and 98%, respectively (Evans et al. [70]).

2.3 Case study

The proposed DHW characterisation method is applied to the residential buildings of the city of Esch-sur-Alzette (Esch), comprising the domestic buildings, the five hotels and the

two nursing homes. The city has a population of 33'487 inhabitants and 14'321 households (Service des travaux municipaux [194]), distributed over 18 districts (Fig. 2.2). The main data source is the city GIS data set (status: June 2015), imported into a PostgreSQL geospatial database (PostgreSQL [175]) using the PostGIS extension (PostGIS Project [174]). The data set contains data on inhabitant and household numbers, year of construction, building footprint and floor number.

In order to assess the impact of DHW energy consumption on low energy and passive buildings (not included in the city assessment due to insufficient data on recent constructions from Statec [202]), these building types are considered specifically. An average inhabitant number for single family buildings (SFB) and multifamily buildings (MFB) of, respectively, 2.98 and 12 as well as an average household number of 1 and 5.48 is used.

The calculations deployed for the case study are described in Section 2.3.1. The results are presented in Section 2.3.2.
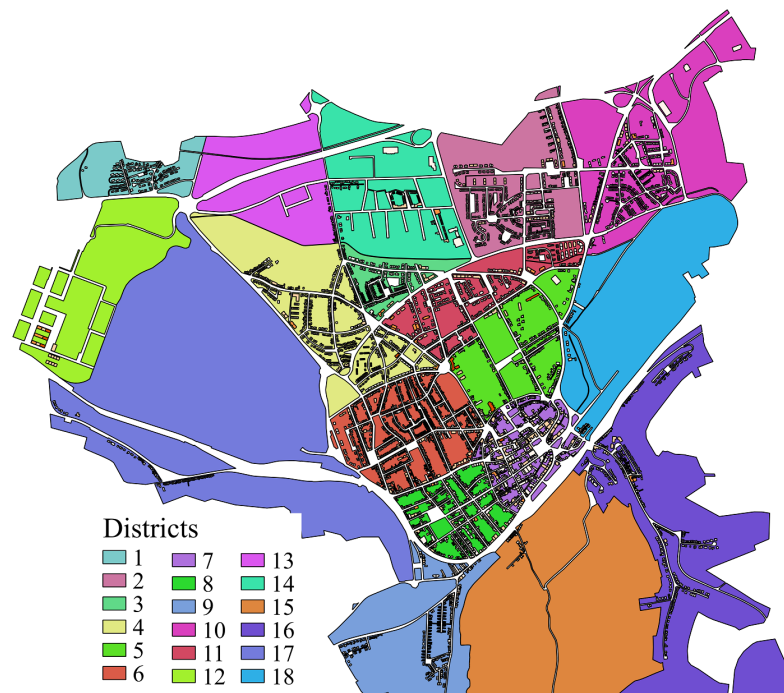
Figure 2.2: Districts of Esch-sur-Alzette

2.3.1 Calculations

In Section 2.3.1.1, the calculation of the various DHW energy demands of the households and lodgings of Esch is set up with the proposed characterisation method. In order to validate the outcomes of the method, DHW energy demand using a surface-related approach is also used. The method to quantify this surface is included in this section. To put the impact of the various DHW streams in relation to the urban heat demand, the total heat consumption

using linear regression is described in Section 2.3.1.2. Section 2.3.1.3 describes how space heating energy requirements are obtained from total heat and DHW energy consumption. The calculation of space heating and utility load of stand-alone heat exchangers in district heating systems are formulated in Section 2.3.1.4. Finally, heat pump energy integration according to various hot water temperature levels is addressed in Section 2.3.1.5.

2.3.1.1 DHW energy consumption

DHW occupant-related method   The end-use types, volumetric flows $\dot{V}_e$, use frequency f_e and duration d_e of Blokker et al. [22] are selected for the present case study, as the data are relatively recent and similar DHW use between the Netherlands and Luxembourg can be assumed as both countries are geographically close and have similar living standards. The end-use types retained are also those generally mentioned in DHW-related publications.

A distribution between efficient and normal shower of 50% is considered. Energy consumption related to shower, bathtub (when available) and bathroom sink use is calculated as a function of inhabitant number. Kitchen sink use (hand washing and hand dish washing) is related to the household number in the building, as indicated by Blokker et al. [22]. A dishwasher occurrence rate of 79% is used (Statec [200]), with the assumption that this type of equipement has its own heating system. 21% of the households are thus doing their dish washing by hand. The French bathtub occurrence rate of 74.4% is applied here. Dishwashers and bathtubs are geoallocated using the RANDOM function in PostgreSQL [175], as more detailed information are not available. The resulting percentage of dishwasher and bathtub occurrence in Esch reaches 78.8% for the dishwasher, and 74.3% for the bathtubs. For the theoretical low energy and passive single family and multifamily buildings , it is assumed that they are equipped with a dishwasher and bathtub.

In hotels and nursing homes, the DHW streams related to the rooms - shower, bathroom sink (washing and shaving) and bathtubs (when occurring) - are considered. The volumetric flows $\dot{V}_e$, use frequency f_e and duration d_e values of Blokker et al. [23] are used. A normal shower type having a volumetric flow of 0.14 l/s is considered. While in hotel five the rooms are equipped with a bathtub and hotels two and three are not, detailed information for hotel one and four are not available. An occurrence rate of 50% is therefore assumed. Eurostat [67] indicates for the Grand-Duchy of Luxembourg, in 2014 for hotels and similar accommodations, a bed-per-room number of 1.9. The number of hotel customers is calculated considering a yearly average bed place occupancy of 35,1% (Eurostat [66]). The year of construction of hotel two is not given in the GIS data set, but as it is a very recent building, it is set to 2012. Nursing homes are only equipped with showers. The nursing homes are also equipped with small kitchen units, but it is not expected that the inhabitants do manual dish washing. The number of occupants is taken from the GIS data set. The values for the various sites are summarised in Tab. 2.7.

Table 2.7: Hotels and nursing homes data

Building	Number of rooms [-]	Daily customer- /patients [-]	Bathtub number [-]	Average room surface [m^2]
Hotel 1	23	15.34	12	18.3
Hotel 2	110	73.36	0	18.0
Hotel 3	22	14.67	0	18.3*
Hotel 4	15	10.00	15	35.0
Hotel 5	20	13.34	10	27.8
Nursing home 1	168	157.00	0	30.5
Nursing home 2	46	32.00	0	30.5*

*assumption

DHW surface-related method and surface quantification   In order to compare the outcomes of the proposed DHW occupant-related model, the DHW energy consumption according to the surface is calculated. These values are generally based on hot water use assessments, where surface data is available Fuentes et al. [81]. For this case study, specific energy consumption values for domestic hot water production of 13.9 and 20.8 kWh/m^{2}a for single and multifamily buildings are assumed (Luxemburgish Parliament [128]). The latter value is also used for mixed-use buildings (MUB). For lodgings, values of 88 kWh/m^2 for nursing homes and 153 kWh/m^2 for hotels are used (Luxemburgish Parliament [126]).

The household floor surfaces of domestic use buildings are obtained by multiplying the footprint area, obtained from the ST_AREA function of PostGIS (PostGIS Project [174]), with the building floor number (including the attic). This method was selected as its outcomes fits best with average household surface values for Esch mentioned in national population census data (Statec [199]). The average surface of single family and multifamily buildings in Esch, 165.65 m^2 and 511.72 m^2 respectively, are considered too for the low energy and passive buildings. For mixed-use buildings and lodgings, this method is not specific enough, as surfaces not related to domestic use would also be included. The reference surface is therefore calculated using the average household surface, obtained from the national population survey (Statec [199]) for Esch, multiplied by the household number (Tab. 2.8).

For hotels and nursing homes, average room surfaces and room numbers are used to calculate the relevant area (Tab. 2.7). Data for hotels are obtained from tourism sites: ONT [156] for room numbers and Booking.com [27] for the calculation of average room surface. As surface data for hotel 3 are not available, the value of hotel 1 is assumed, because both hotels are similar in size and type. Values between 22 to 32 m^2 for 114 rooms and 34 to 42 m^2 for 54 rooms are mentioned for nursing home 1 (Servior [195]), leading to an average room surface of 30.5 m^2. This value is equally used for nursing home 2, as no further data are available. The

Table 2.8: Average household surface for mixed-use buildings in Esch (Statec [199])

Building type, Statec typology	Building type, GIS typology	Households per building	Average surface [m^2]
Collective building, mixed usage	Building, mixed usage	1	136.55
		2-4	66.59
		>4	75.52
Home for adults	Hosting structure	1	74.88
		2-4	25.00
		>4	85.00
Collective building, for living purpose	Student home	1	108.71
		2-4	79.67
		>4	71.81
Other dwelling	Public usage, industry building, commerce or service industry	1	93.33
		2-4	64.80
		>4	54.13

number of rooms for this type of building is taken from the GIS data set of the municipality.

2.3.1.2   Total heat demand using linear regression

A multiple linear regression model is developed to estimate the energy consumption of residential buildings based on measured consumption data. Household budget survey data are obtained from the national statistic agency STATEC (Statec [202]). The model is implemented in the software R (R Core Team [179]) and fitted using the Ordinary Least Squares (OLS) method.

Data from the year 2011 are selected to fit the model due to meteorological condition similar to the average of the region. Only dwellings having natural gas or fuel oil as main fuel are selected. The energy consumption in kWh/a is obtained by multiplying the amount of fuel consumed (m^3 of gas and litres of oil) by suitable calorific values. A distribution of heating systems (traditional and condensing) is assumed based on statistical data to obtain an average calorific value based on national values (Luxemburgish Parliament [128]).

The final sample of observations used to fit the model consists of 794 records (of a total of 1'142) and is obtained by excluding the following items from the original data set: records with missing values; use of other fuels than gas and oil; presence of solar panels; not realistic ratio between energy expenditure and energy consumption, index of errors in the compilation of the survey.

The formulation of the outcome of the linear regression analysis is given by the following equation:

$$ln(y) = \beta_0 + ln(x_{floor}) \cdot \beta_{floor} + ln(x_{occ}) \cdot \beta_{occ} + x_{type} \cdot \beta_{type} + \sum_{i=1}^{5} (x_{period,i} \cdot \beta_{period,i}) + \varepsilon \quad (2.13)$$

where y represents the energy consumption of the dwelling in kWh/a, x_{floor} the useful floor surface in m^2, x_{occ} the number of occupants, x_{type} the type of building (single family building = 1, multifamily building = 0), $x_{period,i}$ the construction period of buildings (factorial variables) and ε the random error term. Some of the variables are logarithmically transformed as they present right skewness and other authors showed how this transformation can substantially improve the performance of the method (Kolter and Ferreira [116]).

Results of multiple linear regression are reported in Tab. 2.9. The coefficient of determination R^2 shows that 54.1 % of the variance is taken into account by the model and it is comparable with the ones obtained by similar studies (Guerra Santin et al. [88]: 42%). The model assumptions were carefully verified and not significant heteroskedasticity and multi-collinearity problems were detected. The equation for multifamily buildings is also applied to mixed-use buildings.

Table 2.9: Statistical summary of the multiple linear regression for residential buildings

Coefficients	Estimate	Std. Error	t value	Significance	
Intercept	6.809	0.206	33.080	<0.0001	***
Floor surface (ln)	0.568	0.047	12.074	<0.0001	***
Number of occupants (ln)	0.106	0.030	3.555	0.0004	***
Type 1: single family house	0.297	0.044	6.675	<0.0001	***
Period 1: <1919	0.220	0.068	3.235	0.00127	**
Period 2: 1919-45	0.148	0.054	2.768	0.0058	**
Period 3: 1946-60	0.159	0.048	3.278	0.0011	**
Period 4: 1961-80	0.204	0.041	4.979	<0.0001	***
Period 5: 1981-95	0.149	0.044	3.388	0.0007	***

Signific. codes: *** < 0.001, ** < 0.01, * < 0.05, . < 0.1, R² = 0.541, Adjusted R² = 0.536

Residual standard error: 0.404 on 785 degrees of freedom, $p - value < 2.2 \cdot 10^{-16}$

Notes: Variables "T2: Multi-family house" and "P6: >1995" assumed as reference.

Coefficients marked with (ln) have been logarithmically transformed.

2.3.1.3 Space heating energy consumption

The space heating energy consumption is calculated by subtracting the DHW energy consumption from the total heat consumption, considering an utility efficiency $\eta_{utility}$ of 90%. For low energy and passive single family and multifamily buildings, specific SH values of 43/22 kWh/m^2 and 27/14 kWh/m^2 are used (Luxemburgish Parliament [128]). As the equations are not applicable to hotels or nursing homes due to difference in user behaviour, the total and space heating energy consumption is only calculated for domestic buildings.

2.3.1.4 Heat exchanger load for district heating systems

The SH load of domestic buildings is calculated using the heating signature calculation (Girardin et al. [85]). As input data, the outdoor temperature $T_{outdoor}$ behaviour as a function of hour t, based on data stemming from the air transport service in Luxembourg (Administration de la navigation aérienne [2]) and structured for the period of Septembre 2011 to August 2011 (to represent the cold season as one continuous curve), is modelled for this case study using polynomial regression analysis, as it yielded the highest R^2 (Eq. 2.14). $t = 1$ thus represents midnight on the first of Septembre, while $t = 8760$ is for the 31st of August at 23:00. The coefficient of determination R^2 reaches 64%.

$$T_{outdoor} = (2*10^{-17})\,t^5 - (4*10^{-13})\,t^4 + (3*10^{-9})\,t^3 - (8*10^{-6})\,t^2 + 0,0003\,t + 16,771 \quad (2.14)$$

A minimum outdoor temperature of -10°C and a threshold temperature of 15°C are considered for the use of the heating signature and therefore the calculation of the space heating load. Equation 2.14 is integrated between the time intervals of 550 and 5'940 hours, where the outdoor temperature is below and above 15°C, respectively. The space heating load of each building is finally obtained by multiplying its reference area with the specific SH load obtained from the heating signature.

With the selected DHW household streams, three types of end-uses are to be considered for the maximal DHW load: bathtub, hand dish washing or shower. The determination of the relevant end-use depends of the occurrence of dishwasher and bathtub in the household. In case a bathtub is available, a load of 25.08 kW is retained. If a dishwasher is not installed, a maximum DHW load of 24.45 kW is considered. Else, the load of the shower is prevailing with 16.30 kW. Following Eq. 2.8 as well as Eq. 2.9 or Eq. 2.10 for households and multifamily buildings, respectively, the load of stand-alone heat exchangers is finally obtained.

In order to compare the results, Eq. 2.7 is applied to calculate the load of an utility combined with a hot water storage system.

2.3.1.5 Energy integration of decentralised heat pump considering various hot water temperature levels

Former works on integrated urban energy optimisation have so far modelled DHW demand as hot water stream at 60°C (Perry et al. [166], Weber [237], Girardin et al. [85], Varbanov et al. [226], Fazlollahi et al. [74]). However, as stated by Girardin et al. [85], various heating utilities providing heat at close space heating and domestic hot water temperatures, like heat pumps and low-grade waste heat recovery, are particularly sensitive to temperature level requirements. Therefore, the impact of the proposed DHW models on the integration of heat pump as heating utility is assessed as example, using the energy integration approach described by Weber [237].

The above-mentioned low energy single family building, equipped with bathtub and dishwasher, is selected as low-temperature SH case study. The space heating load of the building is calculated using the heating signature for the coldest day of the year, with a floor heating system with supply and return temperatures of 30/25°C (Hesaraki et al. [97]). For the first case, a hot water production at 60°C in the storage tank is considered, the load being calculated by dividing the annual DHW energy consumption by 8670 hours. In the second case, a temperature of 50°C is used, as it has been showed that for new or renovated buildings with DHW system volumes below 3 litres and individual DHW feeding pipes, this level is sufficient to avoid Legionella proliferation (Brand et al. [29]). The temperature difference between the condensing side of the heat pump and the hot water is maximum 5K. The evaporation side has a temperature of 5°C (5K below the average of 10°C outdoor temperature), and the electricity consumption is calculated considering a Carnot factor of 55% (Becker et al. [13]). Finally, a price of 0.141 €/kWh is used to calculate the operating costs (Enovos [55]).

2.3.2 Results

As measured DHW energy consumption data are not available to validate the proposed methodology, the results obtained are compared, in Section 2.3.2.1, to values indicated in scientific publications and technical literature addressing DHW. In Section 2.3.2.2 and 2.3.2.3, the DHW-related energy demand is assessed as to the main end-uses and temperature levels. The heat exchanger loads, considered with and without hot water storage, are displayed at district level in Section 2.3.2.4. Finally, the outcomes of the energy integration of heat pumps at different hot water temperatures are presented in Section 2.3.2.5.

2.3.2.1 Validation of outcomes with literature values

The total yearly heat demand of the households in Esch amounts to 189.2 GWh (Fig. 2.3 and Fig. 2.4).

The household DHW energy demand of the proposed methodology is, at city level, 17 % lower than that of the surface-related model (Fig. 2.4). The districts Dellheicht (5), Schlassgoart
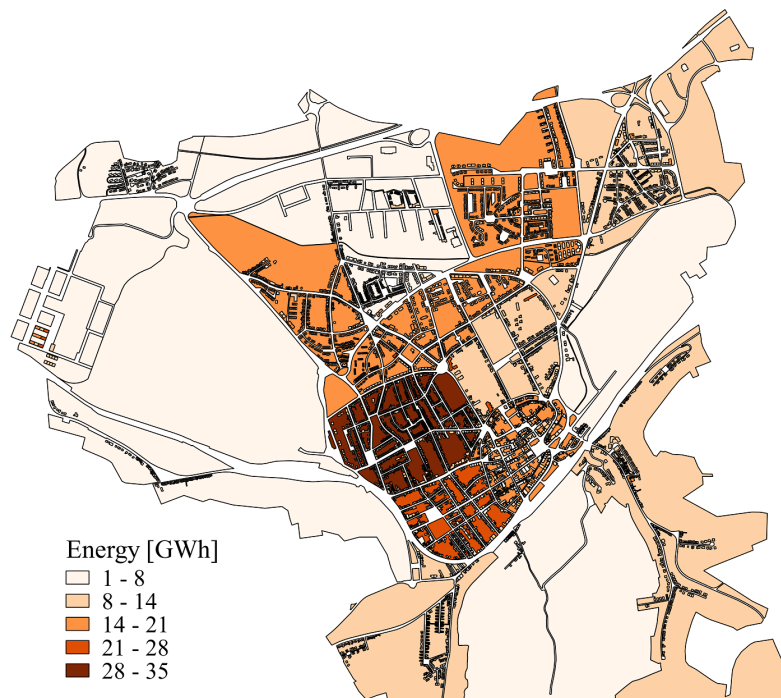
Figure 2.3: Total household yearly heat consumption at district level

(13) and Universiteit (16) have particularly high negative differences, with 48-54% less energy demand. On the other hand, the districts Belval (2) and Raemerich (12) show the opposite behaviour, with the proposed methodology generating energy use values 13-21% higher than the surface-related method. Part of these differences is due to the non-consideration of the heat losses in the proposed characterisation method. Another reason for these differences is probably also due to the reference surface used for the calculations. While using GIS data provides specific information as to floor number and surface per building, areas not relevant to domestic hot water demand (e.g. garages, staircases) are also included, thus leading to an overestimation of the relevant surface and therefore of the energy demand. As represented with the light blue bars, the higher the surface per inhabitant, the higher the difference between the two DHW models. In case the average surface per inhabitant is particularly low, the occupant-related method obtains higher energy consumption values than the surface-related model.

Concerning the hotels and nursing homes, the difference between the two methods is even more important, with the detailed characterisation method reaching only 20% and 9% of the surface-related energy consumption, respectively (Fig. 2.5). Part of this difference can be explained by the fact that the specific DHW energy consumption values are generic and might include additional streams (e.g. room cleaning, bathtub) that are not considered with the proposed model. In addition, an occupancy rate of 35.1% is considered for the hotels, while the surface-related approach assumes an occupancy rate of 100% of the surface.

Considering a hot water temperature of 60°C, a hot water consumption of 33.1 l/capita*day is

30
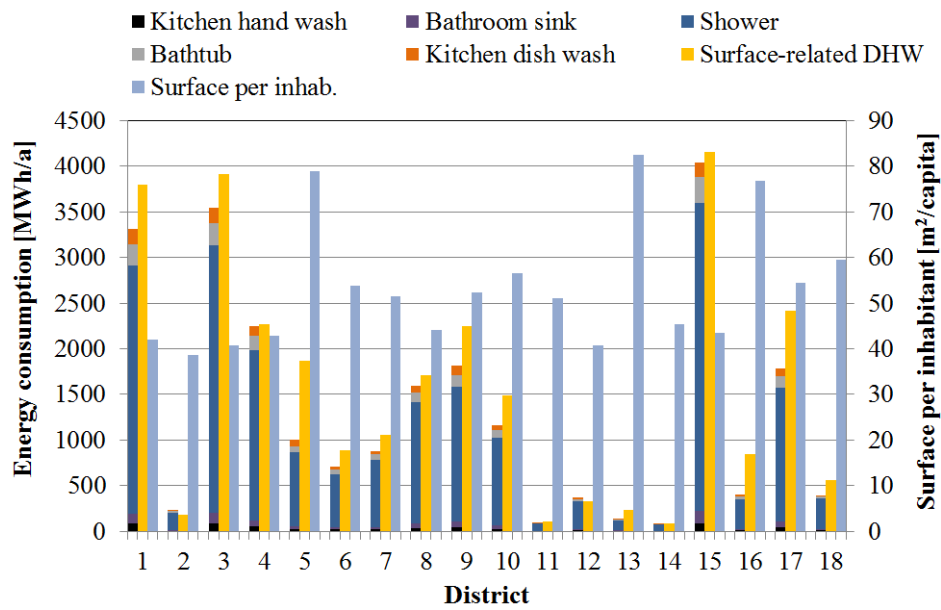
Figure 2.4: DHW-related energy demand and surface per inhabitant (blue column) of households at district level
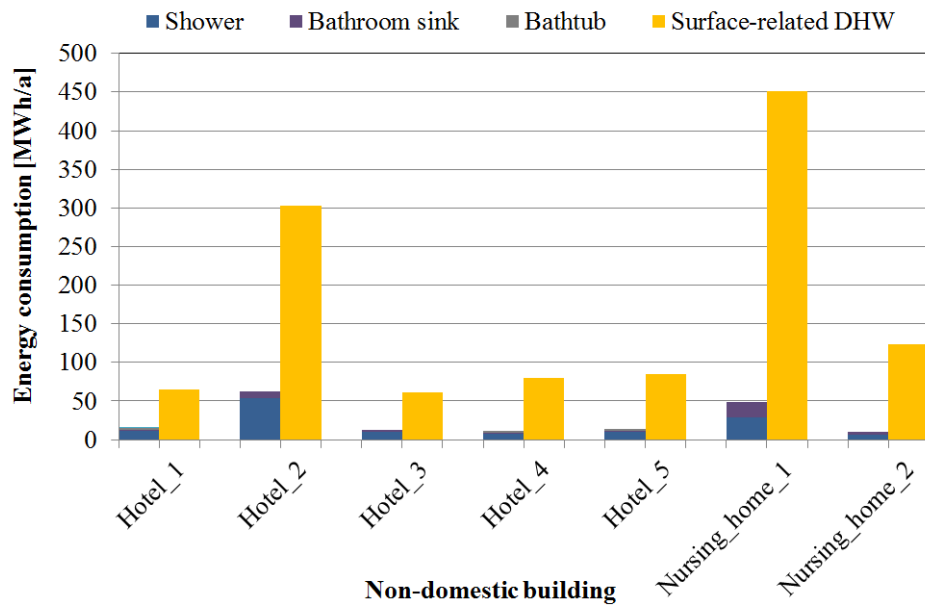
Figure 2.5: DHW energy demand of lodgings

obtained using the proposed DHW streams. Maas et al. [131], Schramek [192] and Girardin et al. [85] mention values of 40 l/capita*day (Luxembourg), 30-60 l/capita*day (Germany) and 50-70 l/capita*day (Switzerland), respectively.

Single family (SFB in Fig. 2.6), multifamily (MFB) and mixed-use (MUB) buildings have a

specific energy demand between 124-172 kWh/m^2, 60-122 kWh/m^2 and 80-123 kWh/m^2, respectively. The outcomes for single family buildings build after 1995 confirms the findings of Maas et al. [131], who obtained an average energy consumption of 131 kWh/m^2 over a sample of 54 buildings built between 1997 and 2007. However, the generated values are lower than those measured by Merzkirch et al. [140], who mentions values of 170 kWh/m^2 and 120 kWh/m^2 for single and multifamily buildings built after 1994 on. This difference is most probably due to the uncertainties of the regression analysis results.

Fuel consumption for heating is, as expected, mostly related to space heating (Fig. 2.6), and decreases for more recent buildings. Concerning existing single family buildings, the fuel conversion losses of the heating utility are higher than the fuel consumption related to DHW. For multifamily and mixed-use buildings, DHW fuel consumption is almost twice as high than the utility losses.
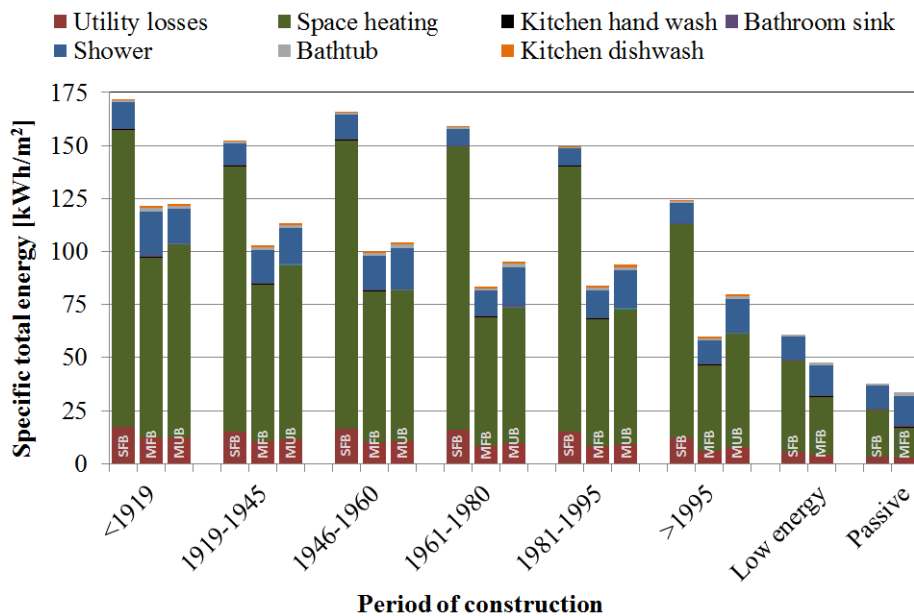
Figure 2.6: Specific thermal energy demand of households (SFB - single family building, MFB - multifamily building, MUB: mixed-use building)

The contribution of the DHW streams to the total heat demand (including utility losses), amounts at city level to 12.3%, while it varies between 6-9% (single family building), 17-23% (multifamily building) and 16-24% (mixed-use) for the considered periods of construction (Fig. 2.7). The relative DHW contribution at city scale should only be compared with other urban systems of very similar number and types of buildings, as this contribution varies according to these parameters. However, the order of magnitude is coherent with the European average of 15.9% (Enerdata [54]). Moreover, Frijns et al. [80] mention an average value of 23% for the Netherlands, and Tooke et al. [216] 22% for Canada. The relevance of DHW energy consumption is 20% and 33% for low-energy and passive SFB and 34% and 49% for MFB. Esch single family and multifamily buildings (mixed usage buildings included) have a specific DHW

energy consumption of 11.75 kWh/m^2 and 17.33 kWh/m^2, while values of 13.9 kWh/m^2 and 20.8 kWh/m^2 are considered at national level (Luxemburgish Parliament [128]).
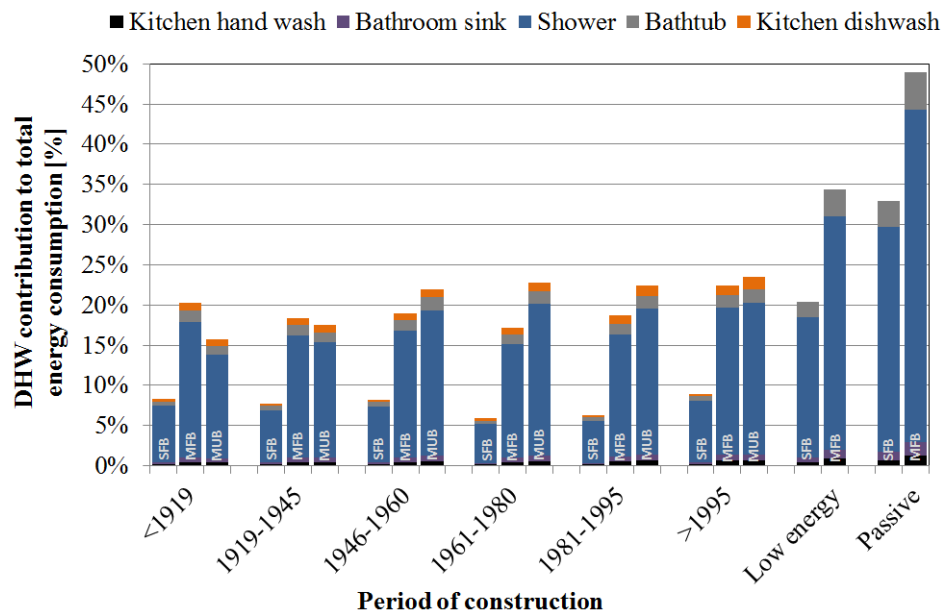
Figure 2.7: DHW energy demand contribution in households (SFB - single family building, MFB - multifamily building, MUB: mixed-use building)

2.3.2.2 Contribution of DHW streams to household energy consumption

In terms of energy consumption, showering represents by far the most relevant DHW stream, which is confirmed by Elias-Maxil et al. [52], contributing between 5-8% (SFB), 14-18% (MFB) and 13-19% (MUB) to the total heat consumption of the buildings (Fig. 2.7). For low energy and passive buildings, this value reaches between 17 and 28 % for single family and between 29 and 41% for multifamily buildings. The bathtub makes up between 2 to 5% of the total heat consumption, and the other streams around 1%.

Related to the total DHW energy consumption, showers contribute between 80 and 84% (Fig. 2.8). The energy consumption of the other DHW streams is comparatively small, with the bathtub contributing to 7%, the manual dish washing between 3 to 7%, the bathroom sink to 3% and hand washing to 2 to 3%. In low energy and passive buildings, shower makes up to 85% of the DHW energy consumption, bathtub 10%, with the remaining streams totalling 5%.

2.3.2.3 DHW temperature level requirements

Considering temperature levels, 0-1% of the total heat consumption is used for domestic hot water use at 35°C (all types of buildings), while 40°C streams represent 5-8%, 15-20% and 14-21% of the heat consumption of single family, multifamily and mixed-use buildings.

Figure 2.8: End-use contribution to household DHW energy demand (SFB - single family building, MFB - multifamily building, MUB: mixed-use building)

DHW demand at 55°C (hand dish washing) lies between 0-2% of the total household heat consumption. For low energy and passive buildings equipped with dishwashers, 1-3 % of the DHW energy consumption is related to 35°C streams, while 19 to 46% of the energy consumption is for 40°C domestic hot water.

Set in relation to the DHW energy consumption, dish washing at 55°C makes between 5 to 7 % of the energy use (Fig. 2.9). 93% of the DHW energy consumption is therefore related to streams at or below 40°C, with 35°C end-use streams (hand wash and washing and shaving) representing around 5%. In low energy and passive buildings, 35°C streams amounts to approximately 6% of DHW energy consumption, while, with the assumption that dishwasher are installed and therefore no 55°C hot water is required, the rest is used for 40°C streams.

2.3.2.4 Heat exchanger load for district heating systems

With the characterisation of the various DHW streams, the load of DH stand-alone heat exchangers of 99% of the single family and 100% of the multifamily and mixed-use buildings is designed according to the DHW demand. Due to the high occurrence of dishwashers and bathtubs, 59% of the utility load of households are sized according to the bathtub load requirement. The stand-alone heat exchanger load of buildings, aggregated at district level (Fig. 2.10a), is between 1.9 and 2.9 times higher compared to a configuration with a hot water storage system (Fig. 2.10b).
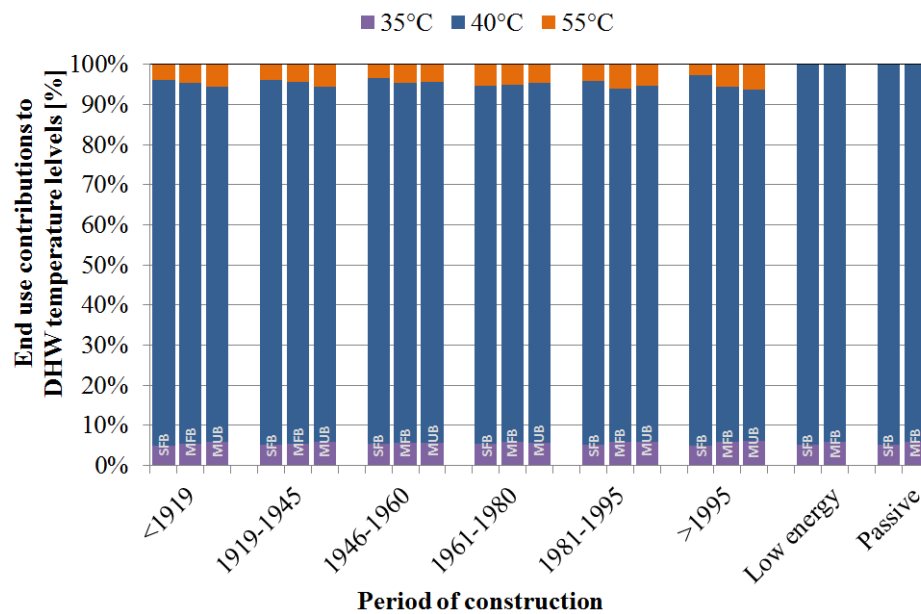
Figure 2.9: Temperature level contribution to household DHW energy demand (SFB - single family building, MFB - multifamily building, MUB: mixed-use building)

(a) Stand-alone heat exchanger

(b) Heat exchanger with hot water storage
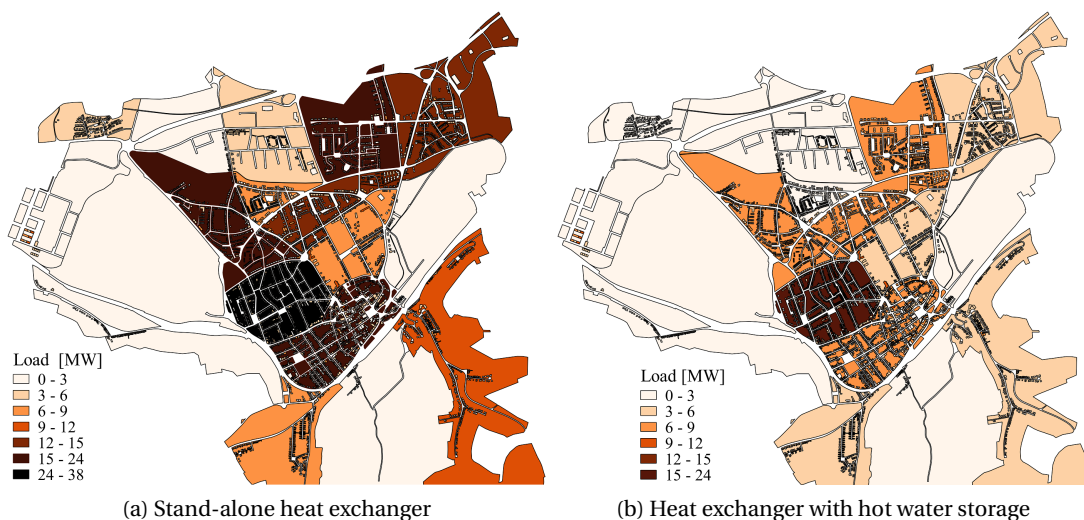
Figure 2.10: Utility heating load at district level

2.3.2.5 Energy integration of decentralised heat pump considering various hot water temperature levels

The results of the energy integration of the heat pump in the low energy single family building is represented as cold (blue line) and hot (red line) composite curves, with the former representing the heating requirements of the building, and the latter the heat pump heating load. As the curves are based on pinch analysis theory (Linnhoff et al. [124]), they are both shifted by

35

half of the assumed minimum temperature difference of 5 K, which explains e.g. the heating requirements temperature of 62.5°C in the figure on the left.

Figure 2.11a represents the configuration with 60°C hot water production. Considering an evaporation temperature of 10°C, the heat pump has a temperature lift of 50 K, which leads to a Coefficient Of Power (COP) of 3.10 and electricity costs of 419 €/year. By reducing the hot water temperature level (Fig. 2.11b) to the minimum required by space heating, DHW end-use temperature levels and hygienic constraints, the COP of the heat pump is increased by 14 % to a value of 3.61, reducing the costs to 359 €/year.

(a) Hot water at 60°C   (b) Hot water at 50°C
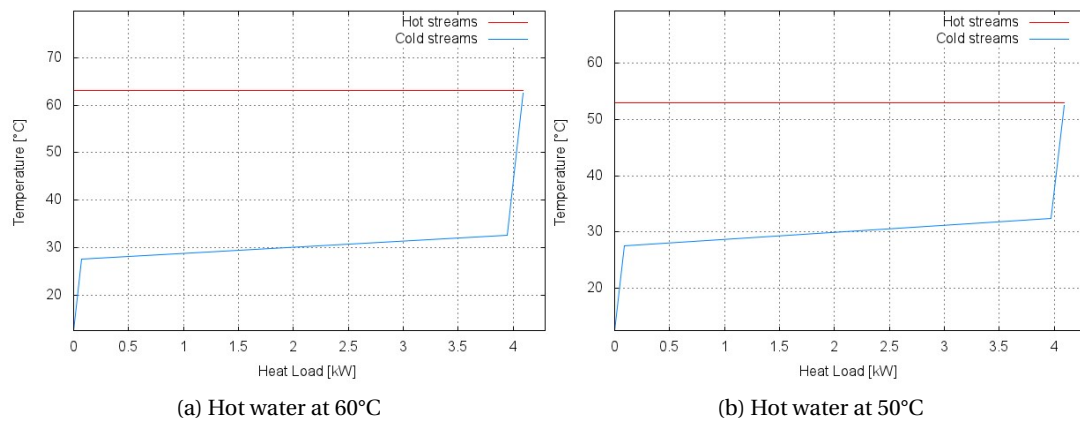
Figure 2.11: Composite curves of a low energy, single family building

2.4   Discussion

A method to characterise and assess DHW streams at city level, down to districts, streets or building blocks, is presented in this work. Although measured data on DHW energy consumption are not available to validate the outcomes of the case study and, therefore, the proposed characterisation method, the related energy demand results are nevertheless confirmed by previous works focusing on DHW urban energy consumption.

The lower DHW energy consumption values of the proposed method, compared to the surface-related method, and the lower specific energy consumption per surface, compared to legislation values, actually highlight an advantage of the exposed method. The observed differences of the case study are most probably due to the inaccuracies in surface estimations, generated with geographical data and therefore including non-heated surfaces (e.g. garages) or actually non-existing areas for buildings with different levels. As an alternative to these estimation, the proposed characterisation approach instead relies on occupant and household or room numbers, data that are usually available from the municipality or other sources. In addition,

as particularly highlighted in the case of hotels in Section 2.3.2.1, using building occupant number instead of surface data as input parameter also allows to reflect the actual level of occupancy of a building. An allocation of DHW energy use to empty or less-occupied buildings is therefore avoided. By relating the DHW consumption to the occupants, the proposed method generates more accurate results, in particular when surface data can only be roughly estimated. The outcomes of space heating energy demand, when calculated at district, street or building block levels, is therefore more precise. Due to the use of a randomising function for the spatial allocation of various end-uses, the proposed method should not be applied at building level. However, this is actually not an issue, as the specific characterisation of the actual DHW end-uses can then be addressed in detail anyway.

One drawback of the proposed DHW characterisation method is the limited input data availability. DHW data specific to the country should be considered, as water use differs according to geographical location and living standards. But information on volumetric or mass flow, use duration, use frequency and end-use occurrence related to the socio-economic level are generally scarce, in particular for non-domestic buildings. Specific data for other types of buildings with relevant DHW demand (e.g. hospitals, sport facilities) are not even available or sufficiently detailed out. This data scarcity also hinders the use of certain methods like Geographically Weighted Regression, which allows a good spatial distribution of end-use occurrence according to living standards, as well as a more precise validation of the proposed characterisation method. Furthermore, the heat losses occuring between the heating utility and the various end-uses are currently not taken into account. An additional weak point is the use of national statistical values to calculate unit occupancy of lodgings, as an equal distribution of customers across the country is assumed. Moreover, the detailed characterisation of the DHW streams implies the risk that some end-uses might be neglected, thus distorting the DHW and SH energy demand outcomes. Finally, the actual user water consumption behaviour, which differs according to age and occupation during the day (Blokker et al. [22]), is not reflected, as this work focuses on yearly assessments.

Further DHW data, covering additional building types, are therefore necessary for a complete application of the proposed characterisation method. Specific DHW-related energy data would also allow a more precise assessment of the validity of the presented work. It is also proposed to include regional or city-level information on hotels and nursing homes directly in the input data set. To avoid the risk of omitting relevant streams, users are encouraged to at least consider the four end-uses described in Section 2.2.2, which are commonly referred to in DHW-related publications. Furthermore, with the proposed detailed characterisation approach, the relevance of heat losses, especially considering large buildings with important distribution lenthgs, should be included to improve the accuracy of the outcomes. A validation of the aggregated DHW demand results with national values is also recommended. Daily user behaviour patterns have already been addressed in former publications and can be referred to in order to conduct assessments with smaller time scale. Globally, as household DHW energy consumption is due to more than 80% to showering only, integrated urban energy assessments and optimisation shall particularly focus on the characterisation on this specific end-use.

The main significance of the proposed DHW characterisation method lies in the simultaneous differentiation and temperature characterisation of various DHW streams at urban scale, where data on inhabitant and household numbers and building types is available. This leads to three main contributions to current integrated urban energy assessments and optimisation methods.

First, the various heating demands of urban systems are better differentiated. This allows to address the impact of specific optimisation measures, like water saving techniques or in-shower, in-building or in-sewer heat recovery solutions. Moreover, the proposed method already generates part of the necessary DHW data (stream types, flows, temperature, etc.) for the modelling and integration of these optimisation measures at urban scale.

Second, the technological scope of integrated energy optimisation of heating utilities in buildings with low temperature space heating is increased. The utility temperature of this type of building is defined by the DHW requirements, as space heating temperature lies below that of DHW end-uses (Brand et al. [29]). These requirements are precisely characterised with the use of the proposed DHW characterisation method, the only limit remaining Legionella proliferation, which, under certain DHW system configurations, can still be avoided with hot water production temperature below 50°C. Therefore, with the decrease of the temperature level requirement from typical 60°C to below 50°C, low temperature utilities, like heat pumps or low temperature waste heat, have a stronger impact in the integrated selection of optimal heating utilities. The reduction in temperature lift profits heat pumping solutions, as their efficiency is improved with lower condensing temperature, and waste heat at a low temperature level can be further valorised as the demand of fitting low temperature heat users is better characterised.

Finally, with the characterisation of the main DHW end-use loads, an additional configuration for district heating transfer stations is available for integrated energy optimisation of urban systems. The characterisation of these loads allows to model stand-alone heat exchangers, an alternative to the heat exchanger and hot water storage unit configuration considered so far in integrated energy optimisation. Previous works have showed that these stand-alone systems can yield equivalent or even better costs and energy efficiency results. The optimal selection between these two configurations should therefore be addressed in future integrated urban energy optimisation works.

3 In-building waste water heat recovery assessment

Abbreviations and symbols

Abbreviations

COP	coefficient of performance
DHW	domestic hot water
FW	fresh water
GIS	geographical information system
GW	grey water
HE	heat exchanger
HW	hot water
MFB	multifamily building
MUB	mixed-use building
SFB	single family building
SH	space heating
WH	waste heat
WW	waste water
WWHR	waste water heat recovery

Symbols

A	heat exchanger surface [m^2]
C	costs [€]
c_p	heat capacity [kJ/kg*K]
d	use duration [s]
dTm	logarithmic mean temperature difference [K]
$dTmin$	minimum temperature difference [K]
f	use frequency [capita*day]$^{-1}$, [household*day]$^{-1}$
I	investment costs [€]
$\dot{m}$	mass flow rate [kg/s]
m	mass [kg]
p	fuel price [€/unit]
PT	payback time [a]

Symbols

$\dot{Q}$ thermal load [kW]

Q energy [kWh]

S yearly operational financial savings [€]

Su subsidies [€]

T temperature [°C], [K]

t time [s]

U heat transfer coefficient [W/m²K]

ε heat exchanger efficiency [-]

η utility efficiency [-]

x_{occ} number of occupants [occupants]

Δ savings [-]

Super- and subscripts

b   building

cond   condensation

e   end-use

evap   evaporation

h   household

ins   installation

m   material

o   occupant

ph   preheated

su   start-up

t   time

to   total

u   household

3.1 Introduction

With a total of 3'441 TWh, 26.8% of the EU28 final energy consumption in 2013 originated from the household sector, coming only second to transport (31.6%) (European Commission [59]). Residential domestic hot water (DHW) consumption represented, with 442 TWh, approximately 16% of the EU household heating demand (Enerdata [54]), energy that is currently lost to the environment with its transfer to the sewers. With the improvement of the building envelope, DHW will have an increasingly important role in energy consumption, with a contribution to total heating demand between 20 and 32% in high efficiency single family buildings and between 35 to almost 50% in multifamily buildings (Meggers and Leibundgut [138], Alnahhal and Spremberg [4], Bertrand et al. [19]).

An option to reduce DHW-related energy consumption in the building, among water flow reduction devices and temperature level decrease, is to recover the heat from the various waste water (WW) streams (in-building solution). Frijns et al. [80] estimated the theoretical maximum waste water heat potential of an Dutch household to 2.16 MWh/a. As showering is the DHW stream with the highest energy demand in a household (Elias-Maxil et al. [52]), most of the works focused on the energy saving and cost impacts of shower heat exchangers (Eslami-Nejad and Bernier [58], Wong et al. [240], Meggers and Leibundgut [138], Guo et al. [89], McNabola and Shields [137], Kordana et al. [117], Torras et al. [217], Deng et al. [46]) or in combination with heat pumps (Liu et al. [125], Chen et al. [39], Wallin and Claesson [234], Dong et al. [49], Gou et al. [86]) and solar energy (Liu et al. [125], Tanha et al. [212]). Works on the use of grey water (GW, waste water not loaded with urine and faeces) streams combined with heat pumps were reviewed by Hepbasli et al. [96]. Recently, Postrioti et al. [176] developed an experimental setup for the assessment of building waste water heat recovery potential, demonstrating that the heat pump could be almost independent from external conditions in case of sufficient waste water rejections. Alnahhal and Spremberg [4] estimated, based on measured data of residential waste water streams, that 30% of the DHW energy demand could potentially be covered by heat recovery in combination with a heat pump. Other publications focused on specific applications, like dishwashers (Paepe et al. [157], Lin et al. [121], Persson [167], Persson and Roennelid [168], Hoak et al. [99], Hauer and Fischer [94], Jeong and Lee [107], Bengtsson et al. [14], Saker et al. [185]), washing machines (Persson [167], Persson and Roennelid [168], Pakula and Stamminger [158], Saker et al. [185]) and barber shops (Sun et al. [209]) or on the experimental evaluation of waste water streams (Ramadan et al. [180]).

However, specific data on mass flow and temperature level of the various residential WW streams is not given, a fact already observed by Meggers and Leibundgut [138]. With the exception of Meggers and Leibundgut [138] and Kordana et al. [117], who focused solely on showers, characterisation methods applied to waste water streams considering inhabitant and household number or end-use occurrences have also not been explored. In addition, the energy saving or cost impacts were not related to the total heating demand while considering varying building characteristics (size, period of construction, etc.). The relevance of these heat

recovery systems, both in terms of financial and energy saving impacts, nevertheless changes according to the specificities of the building (e.g. conventional compared to high efficiency buildings). Moreover, with the exception of Leidl and Lubitz [118], Ni et al. [148], Deng et al. [46], the impact of in-building waste water heat recovery (WWHR) at the level of building blocks, districts or a city has so far not been explored. However, Leidl and Lubitz [118] and Ni et al. [148] applied only used a simplified 'flat-rate' energy saving value or the result from one building type, respectively, instead of aggregating specific building results to the urban scale. Deng et al. [46] calculated the energy savings from shower heat recovery considering the population number, but did not consider other waste water streams. Finally, a preliminary version of this work covered only certain WWHR configurations, and costs as well as the impact of energy integration were not considered (Bertrand et al. [17]).

The objective of this work is to propose a new method for the detailed energy saving and cost assessments of grey water heat recovery systems from the building level and, by data geoallocation and aggregation, to the urban scale. Based on pinch analysis, the method addresses (i) the WW streams characterisation necessary as input to (ii) the thermal load calculation methods, taking into account the number of occupants, the number of households, the appliance occurrences, the building type and the WWHR configuration.

Considering the current methodological shortcomings, the proposed method contributes to existing works with a novel waste water characterisation approach. By geoallocating and defining the waste water streams as a function of occupant and household number, end-use occurrence and building type, the impact of WWHR on the energy consumption is better quantified, which improves the comparison with other energy saving measures. By considering the building age and thus global energy performance, the importance of WWHR in high efficiency residential buildings is demonstrated in detail for the first time. Finally, by aggregating building-specific data, the relevance of grey water heat recovery at the urban scale is more precisely calculated.

The methodology is described in Section 3.2. It is then deployed in two case studies in Section 3.3. Section 3.4 discusses the advantages, shortcomings and contributions of the presented work.

3.2 Method

The energy savings from in-building WWHR systems are quantified in this work using pinch analysis, a recognised assessment method for process integration and more particularly heat recovery (Klemeš [112], Turton et al. [218]). Pinch analysis and its algorithmic formulation (problem table method), initially developed by Linnhoff and Flower [122], assess the heat recovery potential obtained from cooling down hot streams in order to preheat cold streams. As an input, they require the thermal load as well as start and end temperatures of hot and waste water streams. In the detailed assessment being conducted at building scale, temperatures and loads must be characterised according to occupant and household numbers

as well as appliance occurrence (Meggers and Leibundgut [138]). Also, in order to generate realistic load values, actual WWHR systems available on the market are considered. Due to their configuration, the mass flows and temperature levels of the water streams of these systems are constrained, which influence the final heat recovery potential. Their selection is partially limited by space availability and thus dependent on the building type (McNabola and Shields [137]). The operating cost savings are then quantified and the payback time of the various WWHR systems are determined at the building level. By aggregating the geoallocated outcomes to the required scale, the impact of such energy saving measures are finally obtained at the level of a building block, a district or a city (Fig. 3.1).
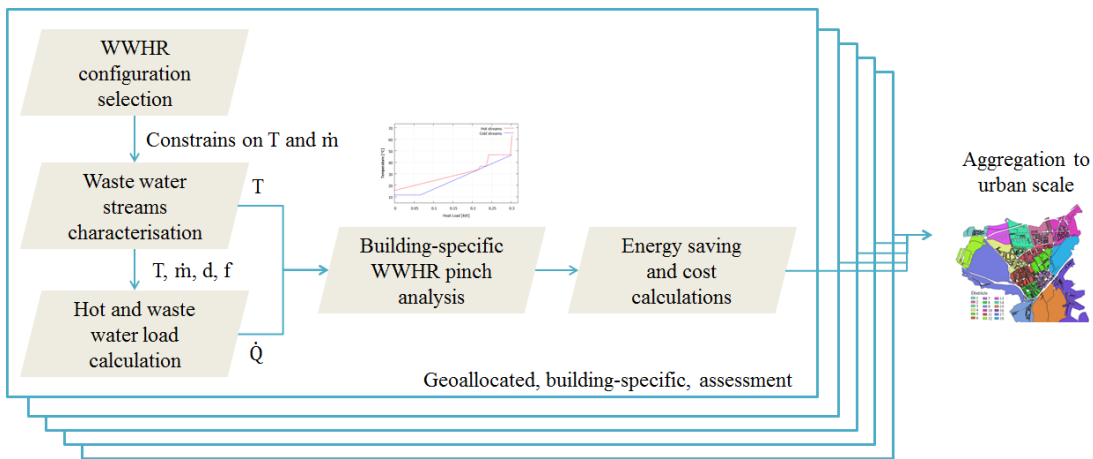
Figure 3.1: In-building WWHR assessment method at the urban scale

3.2.1 Domestic grey water streams characterisation

In order to determine the heat recovery potential of grey water streams for residential DHW end-uses heating, mass flow, duration and frequency of use per capita must be characterised to calculate their thermal load. It is also important to define typical temperature levels and to geographically allocate the various end-uses.

The characterisation and spatial allocation of European DHW streams were addressed in the former chapter (Bertrand et al. [19]). A review of DHW end-use providing reference data on temperature, mass flow, use frequency and duration, considering the inhabitant and household numbers as well as end-use occurrence, was conducted. Similar data for waste water streams is generally very scarce (Meggers and Leibundgut [138]). An equation characterising grey water temperatures as a function of hot and fresh water (FW) temperatures was proposed by Ni et al. [148]. However, the quantification approach of the temperature loss coefficient required by that method is not given. Therefore, grey water streams are characterised based on the work of Bertrand et al. [19], which builds on the characterisation of residential water streams of Blokker et al. [22]. The thermal load of a stream e is obtained from the heat capacity c_p, the mass flow $\dot{m}_e$ and the water temperature difference between exit from the end-use and rejection to the sewer ($T_e^{exit} - T^{reject}$) (Eq. 3.1)

$$\dot{Q}_e = \dot{m}_e \times c_p \times (T_e^{exit} - T^{reject}) \tag{3.1}$$

With the use duration d_e and daily use frequency f_e, the related daily rejected heat is then computed (Eq. 3.2).

$$Q_e = \dot{Q}_e \times d_e \times f_e \tag{3.2}$$

At the building scale, the multiple grey water streams e are attributed to the occupant o (e.g. shower use, washing), the household h (e.g. cloth washing) and the building b (e.g. cleaning of the common areas), with the related rejected heat $Q_{e,o,h,b,t}^{WW}$ of the occupants, $Q_{e,h,b,t}^{WW}$ of the households and $Q_{e,b,t}^{WW}$ of the building. By summing up all the waste water streams e as a function of the occupant and household numbers in the building over a considered period of time (e.g. 365 days for a yearly assessment), the rejected waste heat at building level is determined (Eq. 3.3).

$$Q^{WW,building} = \sum_{t=1}^{365} \left[\sum_e Q_{e,b,t}^{WW} + \sum_h \left(\sum_e Q_{e,h,b,t}^{WW} + \sum_o \sum_e Q_{e,o,h,b,t}^{WW} \right) \right] \tag{3.3}$$

Using Geographical Information System (GIS) data containing geoallocated information on occupant and household numbers for each building, the rejected waste water heat can be calculated at the urban scale.

Regional data on mass flows, durations and use frequencies of water streams are indicated in Chapter 2. Only the data on exit grey water temperature from most of the end-uses, as well as the data from some appliances not connected to the HW circuit (washing machine, dishwasher), are missing for the pinch analysis. A complementary literature review on the few publications mentioning such information is conducted to determine this information.

This approach implies that only reference values are used for the characterisation of the streams. A differentiation between age and gender of the occupants (Blokker et al. [22]), as well as the socio-economic level influencing end-use occurrence (Bertrand et al. [19]) are currently not considered.

3.2.1.1 Bathroom

Concerning shower streams, Wong et al. [240] provided an equation correlating the drain temperature with outdoor temperatures. However, the method was deployed for Hong-Kong, a humid sub-tropical city, with outdoor temperatures of 15°C in winter. This correlation might not be applicable to other climates as it can be expected that in colder climates, the bathroom temperatures remain constant over the year. A limited number of publications nevertheless

provides values for shower temperature differences. Eslami-Nejad and Bernier [58] mention a difference of 4 K for Canada, while Wong et al. [240], Guo et al. [89], Dong et al. [49] indicate ranges of 2-5, 5-8 and 6-8 K for China. A difference of 5 K is used for the heat exchanger (HE) certification in Germany (Passivhaus Institut [162]).

No waste water temperature data stemming from bathtubs is indicated in the literature. To obtain an order of magnitude of the temperature decrease, a difference between 0.5 and 1.5 K was measured under different conditions before and after bathing using a mercury thermometer (Tab. 3.1).

Table 3.1: Bathtub waste water temperatures

Bath duration [min]	Room temp. [°C]	Start temp. [°C]	End temp. [°C]	Temp. difference [K]
20	21	37.0	36.0	1
23	22	43.0	42.5	0.5
26	22	40.5	39.0	1.5
29	22	38.0	36.5	1.5
35	22	39.0	38.0	1

It can be assumed that the grey water temperature of the bathroom sink corresponds to that of the DHW stream, as the distance and retention time in the sink are too short to induce a relevant temperature decrease.

3.2.1.2   Kitchen

Concerning dishwashers, not all of the grey water is rejected at high temperature (Saker et al. [185]). For the prewash phase, the water retains its initial, cold, temperature. Grey water temperature levels varying between 34 and 61°C for the different washing phases (washing, hot rinsing, cold rinsing, etc.) were given by Paepe et al. [157]. However, this publication may be outdated, as a water consumption of approximately 33 l per washing cycle was mentioned by the authors, which is more than twice the water use indicated in other works, e.g. Blokker et al. [22]. Temperature profiles varying between 55 and 60°C are provided by other several authors (Hoak et al. [99], Hauer and Fischer [94], Persson and Werner [170], Bengtsson et al. [14]), while Jeong and Lee [107] presented the GW energy profile as a function of time. Information according to waste water volumes was not provided.

Temperature and water volume profiles for an A rated, 12 place dishwasher from Blomberg/Beko were presented by Saker et al. [185] (Tab. 3.2). The water volumes indicated in the table are averaged to simplify the heat recovery calculations. The prewash water is assumed to be transmitted at ambient temperature to the sewer. The washing phase temperature is confirmed by the findings of Richter [183], who observed that 52% of users select cleaning temperatures at

65°C and higher. The energy of the condensing water (drying phase) is negligible compared to the other phases and is therefore not further considered (Jeong and Lee [107]).

Table 3.2: Dishwasher grey water streams characterisation, according to Saker et al. [185]

Phase [-]	Waste water quantity [kg]	Waste water temperature [°C]
Wash	5.0	65
Cold rinse	3.5	50
Hot rinse	4.0	45

Concerning dish washing by hand, a certain temperature decrease needs to be considered as the plates are initially at room temperature. As no data is available, it is proposed to consider a difference of 5 K. Short uses of the kitchen sink (e.g. hand washing) can be assumed as inducing no temperature losses due to the low duration time.

3.2.1.3   Laundry

Concerning washing machines, Pakula and Stamminger [158] provided data on ownership rate, wash cycle number, water consumption per wash cycle and most frequent wash temperature for several countries and continents (e.g. 40°C in Western Europe). As not all of the machine water is heated up (Saker et al. [185]), national household water consumption statistics to quantify hot grey water volumes must therefore be avoided.

The temperature profile of a washing machine was provided by Persson [167], but the grey water volumes were not given. Ni et al. [148] indicated a hot water (HW) temperature of 49°C for this type of equipment. Saker et al. [185] provided water volume and temperature profiles for a mid-range, A-rated, 7 kg washing machine manufactured by Blomberg/Beko. Of the 65 l water used, 10 l are rejected to the sewer at around 37°C, while the remaining grey water remains generally cold.

3.2.2   Energy assessment of heat recovery configurations

In order to introduce the current shower and grey water heat recovery configurations and to demonstrate their impact on the energy savings, pinch analysis is used in this section for a single family building of 2.98 inhabitants (average number of inhabitants per household from case study 1). The maximum heat recovery is obtained by defining a minimum temperature difference $dTmin$ between the hot and the cold streams. The results are represented in a load/temperature diagram as represented in Fig. 3.2, with the cold composite curve as a blue, bottom curve and the hot composite curve as a red, top curve. The point where both curves are at the distance of the $dTmin$ value is the pinch point. The plots are presented here in

corrected temperatures, deducing from the real temperature the $dTmin$ contributions of the two streams (here $dTmin/2$). The overlapping segment of the two curves indicates the heat recovery potential, while the non-overlapping segments represent the remaining cooling (left segment) and heating (right segment) requirements. As complementary outcomes, the exergetic efficiencies of the various configurations are also presented. It should be noted that the parameters used below are standard values (Schramek [192]), and that user behaviour and single component optimisation (e.g. temperature optimisation), out of scope of the present work, could still lead to further energy and water savings (Cahill et al. [37], Gutierrez-Escolar et al. [90]). In addition, the effects of fouling of the heat exchangers and therefore efficiency losses (Deng et al. [46]) are currently not considered. Finally, due to the urban scope, the calculations are conducted under steady-state conditions.

3.2.2.1 Shower heat recovery configurations

As an input to the pinch analysis calculation, we consider fresh water and sewer temperatures of 10°C (Spur et al. [197], Widen et al. [239]), shower head and tray temperatures of 40°C (Bertrand et al. [19]) and 35°C (Passivhaus Institut [162]), respectively, and a mean water flow of 0.13 kg/s (Widen et al. [239], Neunteufel et al. [147], Bertrand et al. [19]). A theoretical dTmin of 3 K is assumed, which therefore shifts the hot and cold stream curves by 1.5 K.

Using mass balance and pinch analysis, the DHW shower production could be covered, in theory, to 74% by heat recovery when considering fresh and waste water with identical mass flows (balanced flow), with the waste water exiting at 11.5°C (corrected temperature at the bottom left point where the two curves do not overlap, Fig. 3.2). However, the fresh water temperature would reach 32°C instead of the required 40°C, which implies a further mixing with hot water. This is not feasible, as the maximum fresh water mass flow is already reached.
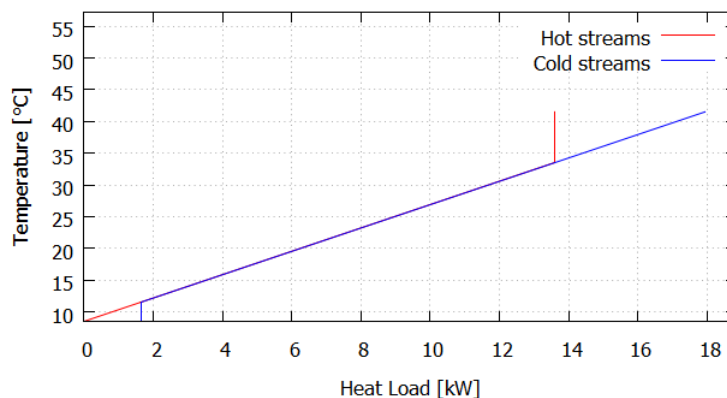
Figure 3.2: Pinch analysis diagram - balanced conditions

Three concrete configurations are usually considered for the production of shower hot water (Slys and Kordana [196]). The first system (configuration 1) uses the waste water to preheat the hot water flow of the shower (Fig. 3.3a). The temperature of 40°C is then realised by mixing

with cold water. Due to mass balance, the heat recovery in this configuration implies a lower hot water flow of 0.09 kg/s. In this case the heat recovery reaches 49%, with the grey water leaving the heat exchanger at the corrected temperature 19°C instead of 11 °C (Fig. 3.3b).

(a) System

(b) Pinch analysis diagram
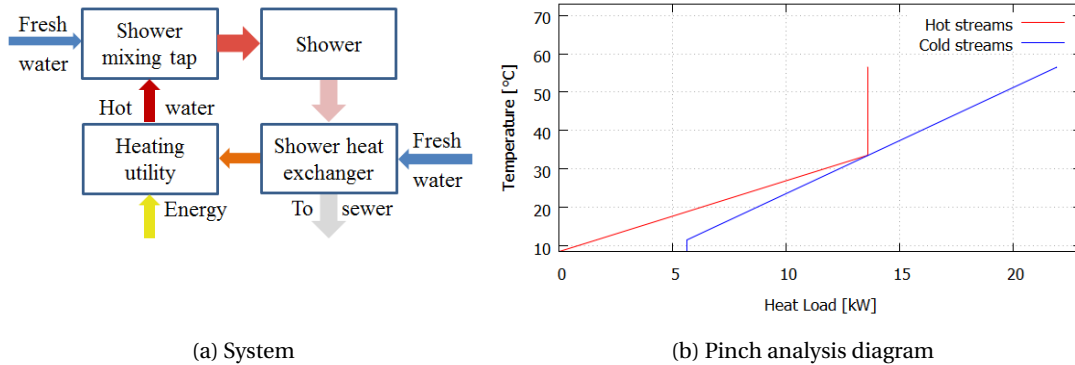
Figure 3.3: Configuration 1

A second option (configuration 2) is to preheat the full shower mass flow of 0.13 kg/s, and to split it between a preheated 'cold' water stream and a preheated water stream used for hot water production (Fig. 3.4a). The heat recovery reaches 74% and the waste water exits at the corrected temperature 11.5°C (Fig. 3.4b).

(a) System

(b) Pinch analysis diagram
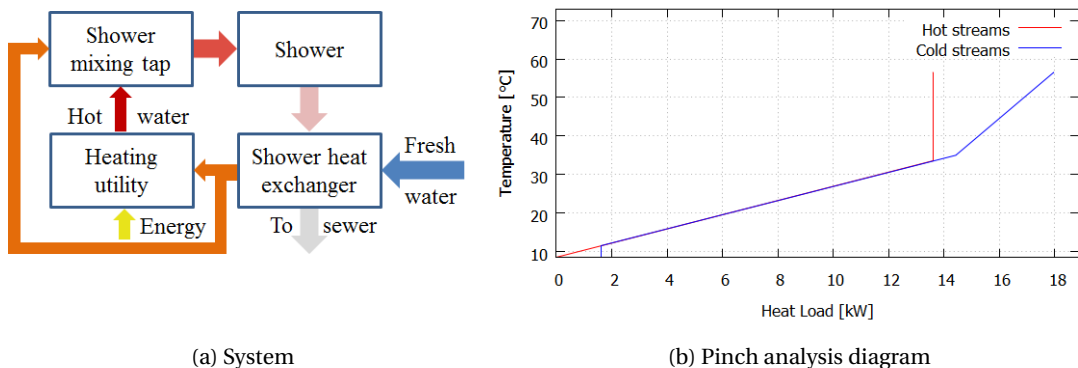
Figure 3.4: Configuration 2

In configuration 3, only the cold water is preheated (Fig. 3.5a). The hot water demand is reduced, as the 'cold' water has a higher temperature. Similarly to configuration 1, this configuration is constrained by the cold and hot water mixing, as the mass flow and temperature after mixing must match the shower flow and temperature requirements. After heat recovery, pinch analysis indicates that the waste water is at corrected temperature 19 °C and the heat recovery corresponds to 48% of the heating load (Fig. 3.5b).

A small minimum temperature difference dTmin of 3 K and immediate heat transfer are assumed above, in order to compare the efficiency of the various configurations. However,

(a) System

(b) Pinch analysis diagram
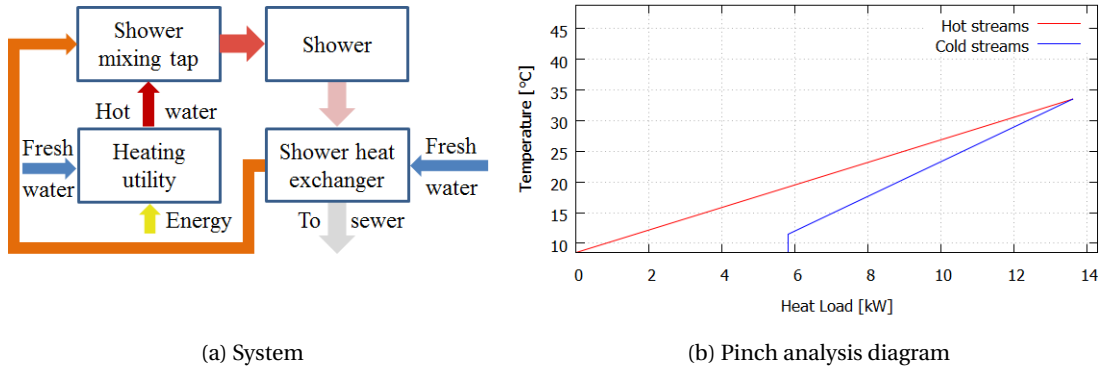
Figure 3.5: Configuration 3

the energy savings by shower heat recovery are also dependent on the heat exchanger type, which influences both heat transfer and duration of the exchange. Actual shower HE are either mounted horizontally in the shower tray or vertically as an element of the waste water piping. Horizontal heat exchangers have a short start-up phase (period where heat exchange does not occur yet) of 5 seconds for the HE (Passivhaus Institut [163]), while additional 10 seconds for the circulation duration through the shower pipe and tray is further assumed for the present calculations. However, due to their small surface leading to a $dTmin$ between 12 and 15 K, their heat transfer efficiency is low (balanced flows of 0.13 kg/s). Vertical HE yield a higher heat recovery efficiency due to a larger exchange surface but the $dTmin$ is still between 9 and 10 K (source: Wagner Solar GmbH, passiv.de). Tanha et al. [212] measured a start-up phase of 90 seconds.

The implementation of the different HE and heat recovery configurations is also constrained by space availability imposed by the building type and by the location of the heating utility. Vertical HE require one to two meters of space below the shower tray, which limits their installation as a retrofit solution in multifamily buildings or single family houses with showers at the ground floor (McNabola and Shields [137]). They are mostly combined with configuration 1 and 2, as the component can be installed close to the heating utility for hot water preheating. Horizontal heat exchangers have lower space requirements and are easily installed, even in existing buildings (Schnieders [191]). They are mostly intended for systems where preheated fresh water is mixed with hot water (configuration 3) and a direct connection to the heating utility is not available.

Taking into account the actual HE efficiencies and start-up durations as well as implementation constraints, the daily shower energy savings ΔQ_{shower}, expressed in kWh, can therefore be determined at building level (Eq. 3.4):

$$\Delta Q_{shower} = \frac{\dot{m}^{ph} \times c_p \times (T^{ph} - T^{FW}) \times (t_{to} - t_{su}) \times f \times x_{occ}}{3600} \tag{3.4}$$

with $\dot{m}^{ph}$ the preheated mass flow in kg/s, c_p the heat capacity in kJ/kg*K, T^{ph} and T^{FW} the preheated and fresh water temperatures in °C, the duration $(t_{to} - t_{su})$ in s, with t_{to} being the total and t_{su} the start-up durations, the daily shower frequency f per person in (day*capita)$^{-1}$ and the number of inhabitants x_{occ}. Values for shower mass flow, duration and frequency in various EU countries are given in Bertrand et al. [19]. The preheated mass flow and temperature variables of the various configurations are obtained by energy and mass balances depending of the considered configuration and heat exchanger type (Appendix A.1).

Using Eq. 3.4, and considering a household of 2.98 inhabitants, a vertical heat exchanger implemented in configuration 1 and 2 (with estimated T^{ph} of 21 and 26.5°C) yields daily energy savings of 1.0 and 2.2 kWh/day, respectively, which represents 21 and 45% of the daily shower energy requirements. The use of a horizontal heat exchanger combined with configuration 3 would result in savings of 402 kWh/a, which is identical to the energy savings indicated by McNabola and Shields [137] when assuming the same use frequency. The exergy efficiency of the systems, based on the exergy values on waste water and preheated streams with a reference temperature of 10°C and considering the various start-up durations, is 11%, 37% and 15%, respectively.

3.2.2.2 Grey water heat recovery configurations

The pinch analysis at building level is conducted with the streams described in Tab. 3.3, where data from Bertrand et al. [19] and Section 3.2.1 are compiled. It is assumed that the building is equipped with a bathtub and a dishwasher with an own internal heating system.

Pinch analysis was initially developed for industrial processes considering continuous operation. For the heat recovery analysis conducted here, it is necessary to consider mean flows of water representing the mean power over its time of use. The DHW, grey water and hot water stream loads are therefore obtained by summing the daily energy values and averaging these over one hour, as expressed in Eq. 3.5-3.7.

$$\dot{Q}_e = \frac{\sum_{x_{hhold}} \sum_{x_{occ}} (\dot{m}_e \times d_e \times f_e) \times c_p \times (T_e - T^{FW})}{3600} \tag{3.5}$$

$$\dot{Q}^{GW} = \frac{\sum_{x_{hhold}} \sum_{x_{occ}} (\dot{m}_e^{GW} \times d_e \times f_e) \times c_p \times (T^{GW} - T^{sewer})}{3600} \tag{3.6}$$

$$\dot{Q}^{HW} = \frac{\sum_{x_{hhold}} \sum_{x_{occ}} (\dot{m}_e^{HW} \times d_e \times f_e) \times c_p \times (T^{HW} - T^{FW})}{3600} \tag{3.7}$$

with x_{occ} and x_{hhold} the inhabitant and household numbers, T_e, $\dot{m}_e$, d_e and f_e the temperature, mass flow, duration and frequency of use of the end-uses e, c_p the heat capacity and the

Table 3.3: Domestic hot and grey water streams (Bertrand et al. [19])

Stream [-]	Appliance [-]	Use level [-]	End-use temp. [°C]	Drain temp. [°C]	Mass flow [kg/s]	day]	Frequency [1/capita*day] [1/h-hold*day]
Hand wash	Kitchen sink	Household	35	35	0.08	15	3.15
Washing and shaving	Bathroom sink	Inhabitant	35	35	0.04	40	1.35
Shower	Shower	Inhabitant	40	35	0.13	510	0.70
Bath	Bath	Inhabitant	40	39	0.20	600	0.044
Wash	Dishwasher	Inhabitant	n.a.	65	0.08 (5kg)	60	0.30
Cold rinse	Dishwasher	Inhabitant	n.a.	50	0.06 (3.5kg)	60	0.30
Hot rinse	Dishwasher	Inhabitant	n.a.	45	0.07 (4kg)	60	0.30
Cloth washing	Washing machine	Household	n.a.	37	0.17 (10kg)	60	0.45

n.a. - not applicable

various fresh water, grey water, sewer and hot water temperatures T^{FW}, T^{GW}, T^{sewer}, T^{HW}. Complementary equations specific to the various configurations assessed below are given in Appendix A.2.

When considering the immediate heat transfer between the specific DHW and WW streams, represented in the pinch analysis of Fig. 3.6, 80% of the DHW heating load would be covered by heat recovery, with the grey water being rejected at 14°C. However, DHW demand and WW rejection do not occur simultaneously and a storage (and according control) systems are necessary for heat recovery.

One option is to use a grey water storage tank for hot water production (configuration 4, Fig. 3.7a). This system reduces the DHW-related energy consumption by 52%. The water is stored at 37°C and rejected to the sewer at a corrected temperature of 21°C (Fig. 3.7b). The exergy efficiency of the system, with 10°C as a reference temperature, reaches 58%.

Another option is to use a grey water tank for fresh water preheating and a utility producing the DHW only at the required temperature (configuration 5, Fig. 3.8a). The necessity of hot water production at 55°C is linked to hygiene constraints (limitation of Legionella proliferation), but can be avoided in buildings where the volume of the DHW distribution system does not exceed 3 l and individual pipes are installed (Brand et al. [29]). With a dishwasher, the actual DHW end-use temperatures do not exceed 40°C (Bertrand et al. [19]). The DHW energy consumption can be reduced by 80%, with the grey water rejected at 14°C and an exergy efficiency of 88%
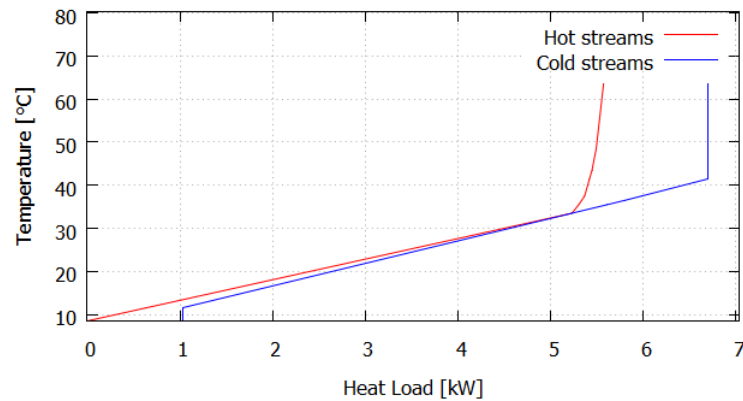
Figure 3.6: Pinch analysis diagram - DHW and WW streams
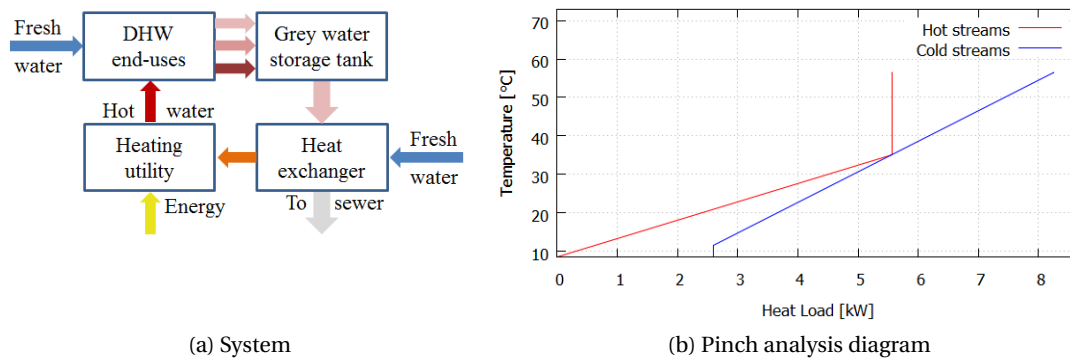
(a) System

(b) Pinch analysis diagram

Figure 3.7: Configuration 4

(Fig. 3.8b). While yielding a high efficiency, this configuration is difficult to implement, as it requires direct connections between utility and DHW end-uses, which would drastically increase installation and equipment costs.

Finally, grey water streams can also be used for hot water production and storage (configuration 6, Fig. 3.9a). Using mass balance and pinch analysis, while considering a HW temperature of 55°C, heat recovery would cover 55% of the DHW heating, with the grey water streams leaving at a corrected temperature of 20°C and a exergy efficiency of the system of 63% (Fig. 3.9b).

For urban assessments comprising several buildings, the daily energy savings from grey water heat recovery ΔQ_{grey} is computed for each building using the problem table method (Linnhoff and Flower [122]), the algorithmic form of the pinch analysis. The results are then aggregated to the required scale (building block, street, district, city).

(a) System

(b) Pinch analysis diagram
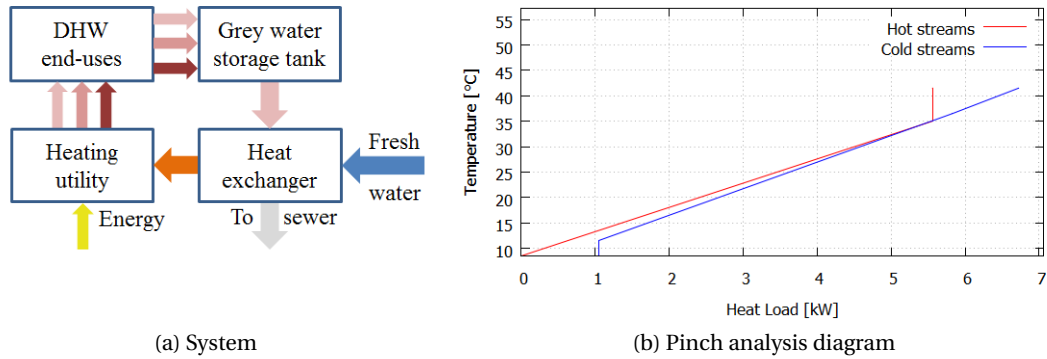
Figure 3.8: Configuration 5

(a) System

(b) Pinch analysis diagram
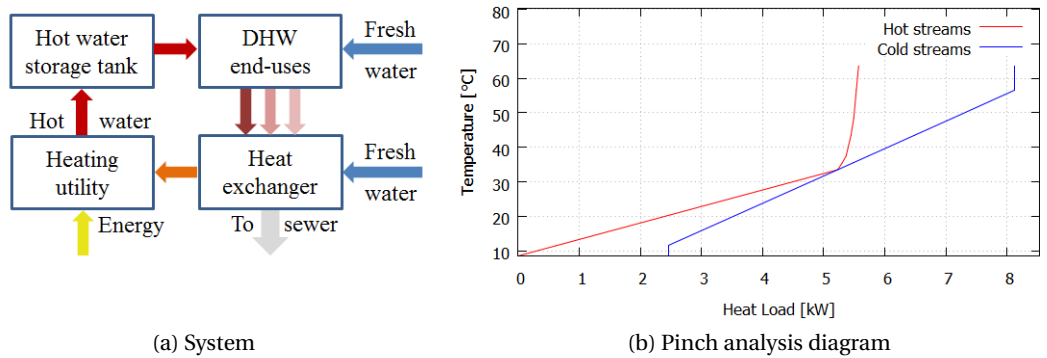
Figure 3.9: Configuration 6

3.2.3 Costs calculations

The investment costs I are obtained as the sum of material and installation costs C_m and C_{ins} (Eq. 3.8).

$$I = C_m + C_{ins} \tag{3.8}$$

For shower heat exchangers, only the additional costs, compared to a normal shower tray or inline drain system, should be considered, to avoid including the cost of the normal drain system.

To calculate the investment costs of the heat exchanger of the grey water configuration, its power is calculated considering the grey water stream with the highest power (usually linked to the bath or the dishwasher) multiplied with a simultaneity factor of 1.15 for single family buildings (Schramek [192]). Concerning multifamily buildings, the simultaneity factor given by Gaderer [84] for DHW demand is multiplied with the sum of the maximum grey water load $\sum_u \dot{Q}_{u,max}^{WW}$, with u the number of households in the building (Eq. 3.9).

$$\dot{Q}^{WW,building} = [0.02 + 0.92 u^{(-0.58)}] \times \sum_u \dot{Q}^{WW}_{u,max} \qquad (3.9)$$

The yearly operation savings S are proportional to the energy savings ΔQ, the utility efficiency η and the fuel price p (Eq. 3.10). As raised by Bianco et al. [20], energy prices can strongly increase or decrease according to market changes (e.g. increased demand or oversupply), thus making short to mid-term price estimation a difficult task. The current formulation of the method allows the user to select its own energy price definition, i.e. an average price taking into account a potential fluctuation (Kordana et al. [117]) or the energy price of a given reference year (Tanha et al. [212]).

$$S = \Delta Q \times \eta \times p \qquad (3.10)$$

The payback time PT in years is the ratio of investment costs I and operating savings S (Eq. 3.11).

$$PT = I/S \qquad (3.11)$$

The subsidies Su necessary to reach a given payback time PT is finally obtained with Eq. 3.12.

$$Su = I - (S \times PT) \qquad (3.12)$$

3.3 Case studies

In order to highlight the diversity of results encountered at city scale (compared to the single family building-related assessments conducted in Section 3.2), two case studies, subdivided into several scenarios to assess different optimisation configurations as to their impact on the total heating demand, are deployed in this work. The characterisation as well as energy savings and cost calculation methods are first applied to the existing residential buildings of the city of Esch-sur-Alzette (case study 1). As the necessary data for the quantification of heating demand of the low energy and passive (high efficiency) residential buildings of the city are not available, and as grey water heat recovery could be of particular relevance for these buildings, these are specifically assessed as to potential energy savings in a second case study (case study 2).

3.3.1 Common input data

Temperatures of 10°C and 55°C are assumed for the fresh and hot water, respectively (Spur et al. [197], Schramek [192], Widen et al. [239]). The grey water streams are characterised according

to Section 3.2.1 and summarised in Tab. 3.3. Use frequencies of dishwashers and washing machines are taken from Blokker et al. [22] and Pakula and Stamminger [158], respectively. The waste water mass of the streams of these two utilities are considered to be rejected within one minute (Saker et al. [185]).

To limit the scope of the case studies, two types of heat recovery systems are deployed: a horizontal shower heat exchanger (configuration 3) for scenario 1.1 and 2.1 and a grey water heat recovery system for hot water preheating (configuration 6) for scenario 1.2, 2.2 and 2.3, as the majority of the heating systems are equipped with a hot water storage tank (Schramek [192]). The shower heat exchanger is a Ecoshower 900/DSS showerdrain channel WWHR model 900/4, with an efficiency of 54% under stead-state conditions (Passivhaus Institut [163]). With a pipe length of 6.8 m and an external diameter of 0.016 m, the power under unbalanced conditions is 4,86 kW (source: Wagner Solar GmbH). Using energy and mass balance, the fresh water exits the heat exchanger at a temperature of 27°C with a mass flow of 0.07 kg/s. The energy savings related to the grey water heat recovery system are calculated at building level using the problem table method (Linnhoff and Hindmarsh [123]). A minimum temperature difference of 5K is considered for the heat exchanger.

3.3.2 Retrofit solutions at urban scale

3.3.2.1 Specific input data

The DHW requirements of the city, based on GIS data (Service des travaux municipaux [194]) converted into a PostgreSQL database (PostgreSQL [175]), have been characterised in a former work (Bertrand et al. [19]). The occurrence of the various waste water streams are related to the use of the multiple DHW end-uses in each building. 78.8% of the households are equipped with a dishwasher (Statec [200]). It is assumed that these dishwashers have an internal heating system and are thus not connected to the hot water system. The remaining 21.2% do the dish washing manually, with an end-use temperature of 55°C, a mass flow of 0.13 kg/s, a duration of 48 s and a frequency of 3.15 uses per household per day (Blokker et al. [22], Schramek [192]). The waste water is assumed to be emitted to the sewer at a temperature of 50°C (5K heat losses).

The additional costs of a horizontal shower heat exchanger (scenario 1.1), compared to a normal drain system, are between 150 and 300 €. Average investment costs of 225 € are therefore considered for horizontal heat exchangers. Typical installation costs are around 100-300 €; an average value of 200 € is used here (source: Wagner Solar GmbH). The investment costs for the grey water heat recovery system (scenario 1.2) are summarised in Tab. 3.4. The costs for the prefilter, the 3-way valve to avoid cold streams in the storage tank and the sensor are market prices (source: Dehoust). The specific price of heat exchangers considers a price increase of 50% to reflect the necessity of a double-wall construction as safety measure to avoid a mixing of grey water with fresh water (source: Wiltec). Additional piping and installation

costs are estimated at 50 € and 200 €, respectively (source: Wagner Solar GmbH). A utility efficiency of 90% is applied. Following the input of local partners regarding short-term energy price fluctuations and the need for clear communication of the outcomes to a larger public, it was decided to use the reference energy price of 2015, which reached 0.043 €/kWh (including VAT, source: Sudgaz). All other values are without VAT (3% for construction projects).

Table 3.4: Cost parameters for grey water heat recovery

Component [-]	Unitary price, excluding VAT [€]
Prefilter	330
Heat exchanger	45 €/kW
3 way valve	200
Sensor	70
Piping	50
Installation costs	200

3.3.2.2 Results

Energy savings   Figure 3.10 (scenario 1.1) and Fig. 3.11 (scenario 1.2) represent the relative energy savings (light blue) and remaining DHW energy requirements (dark blue), related to the total fuel consumption for heating (covering space heating, DHW and utility inefficiency losses). The percentages indicated are the savings, relative to the total fuel consumption, obtained from the implementation of the HR systems.

With a horizontal heat exchanger, energy savings between 1.4 and 2.2% in single family buildings, as well as between 3.8 and 5.7% in multifamily and mixed-use buildings can be reached (Fig. 3.10). For a three inhabitants, single family house, the energy savings would reach 402 kWh/a. An average multifamily building of 12 inhabitants, 5.5 households, would save 1'617 kWh/a. 23% of the showering energy would thus be saved. These outcomes are in line with the values indicated by McNabola and Shields [137] when recalculated for a shower frequency of 0.7 1/day. Wong et al. [240] mention savings between 4 and 16% for a single-pass HE and Frijns et al. [80] indicate natural gas savings between 30 and 40%. Guo et al. [89] reached shower energy savings of 50% with a novel design for the heat exchanger and conducting the assessment under laboratory conditions.

With grey water heat recovery for hot water preheating, savings between 3.0 and 4.5% in single family buildings and between 8.0 and 11.9% for multifamily and mixed-use buildings are obtained (Fig. 3.11). A three inhabitants, single family house, would save in average 1'059 kWh/a, while 4'282 kWh/a would be saved in a multifamily building of 12 inhabitants, which represents approximately 50% of the DHW energy demand. Compared to the theoretical maximum heat recovery potential of 2'160 kWh/a indicated by Frijns et al. [80] for households
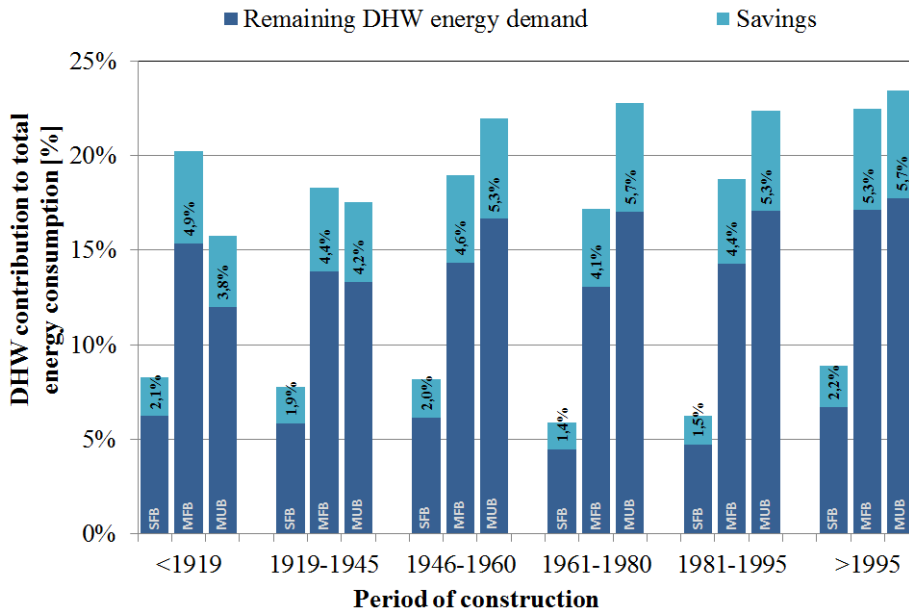
Figure 3.10: Scenario 1.1: horizontal shower heat exchanger - relative energy savings (SFB – single family building, MFB – multifamily building, MUB - multi-use building)

in the Netherlands, it appears that, by using real input data and considering actual WWHR system configurations, 49% of these theoretical savings are achieved.
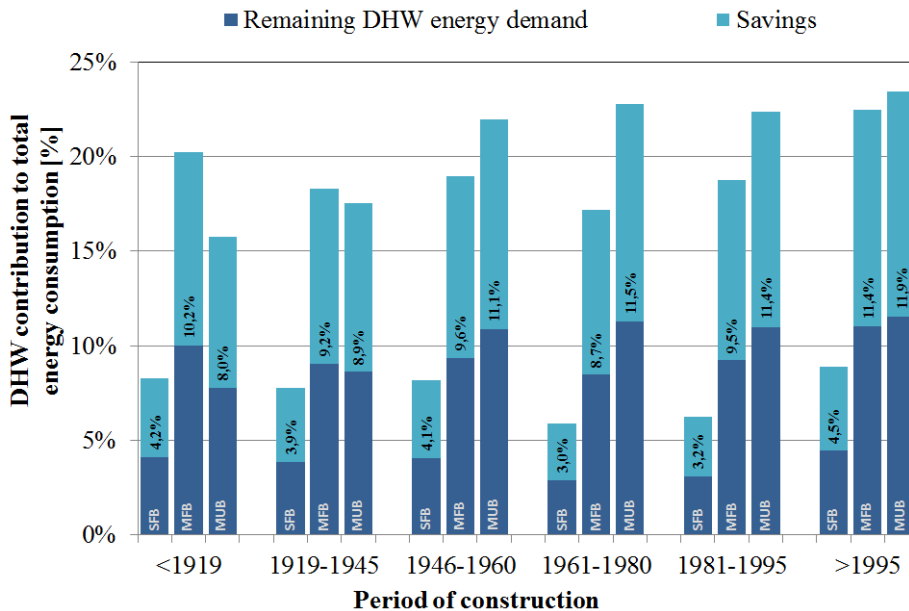
Figure 3.11: Scenario 1.2: grey water heat recovery - relative energy savings (SFB – single family building, MFB – multifamily building, MUB - multi-use building)

Payback time For the assessed heat recovery systems, the investment costs and cost savings depend on the energy price, the numbers of inhabitants and the number of households. For one-household buildings (Fig. 3.12), considering the reference natural gas price indicated above, shower heat recovery for singles or couples leads to payback times above 50 years, while the average household (three inhabitants), would see a payback time of almost 18 years. From 6 inhabitants on, the payback time falls below 10 years. For the grey water heat recovery of scenario 1.2, the payback time is almost twice as high as scenario 1.1. A payback time of 10 years is reached for households of at least 13 inhabitants. Single family buildings with 12 inhabitants are not occurring in the city and are therefore not displayed. With increasing household numbers per building, the average payback time of shower HR does not change for the households, as displayed for a five households building (Fig. 3.13). The payback time for three inhabitants per 5 households remains at 18 years. The payback time of grey water heat recovery falls below 10 years for 18 occupants.
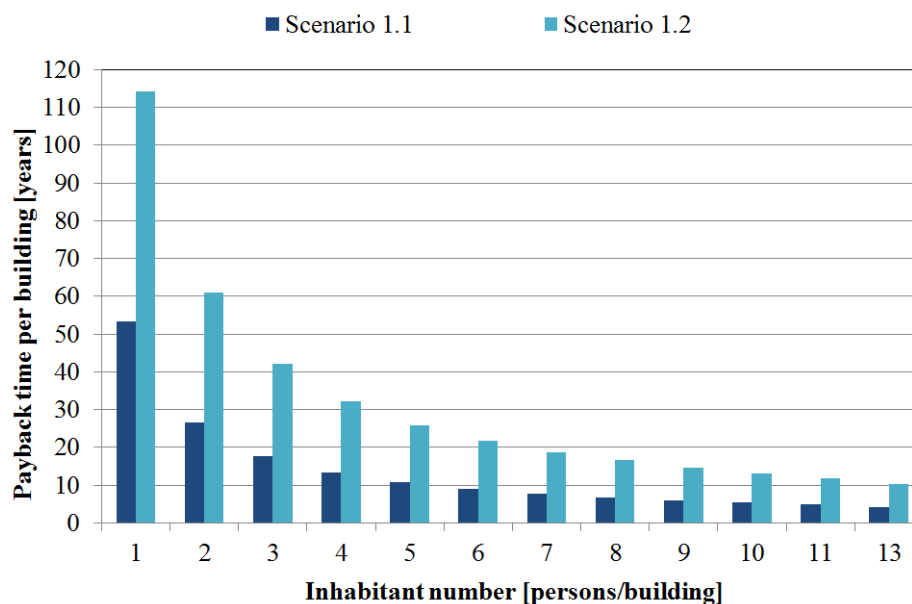
Figure 3.12: Average payback time for one household buildings

The direct comparison of these outcomes with the results of similar works is generally not recommended due to strongly varying conditions (e.g. energy prices, equipment and/or installation costs, use frequency and duration). Nevertheless, it should be mentioned that Kordana et al. [117] obtained, with an energy price of 0.16 €/kWh, a payback time for vertical shower heat exchangers of 7, 5 and 4 years for a Polish household with 3, 4 and 5 inhabitants, respectively. Values between 4 and 5 years for a 4 persons household are calculated by Slys and Kordana [196]. Tanha et al. [212] estimated the payback time of a vertical shower heat exchanger system for a four inhabitant house installed in Canada to be 5.6 years (with an electrical heater at 0.136 $/kWh) and 17 years (with a natural gas boiler at an energy price of 0.046 $/kWh). McNabola and Shields [137] indicated a paypack time of 5 years, with an energy price of 0.18 €/kWh. The much lower payback times can, at least partially, be explained by the
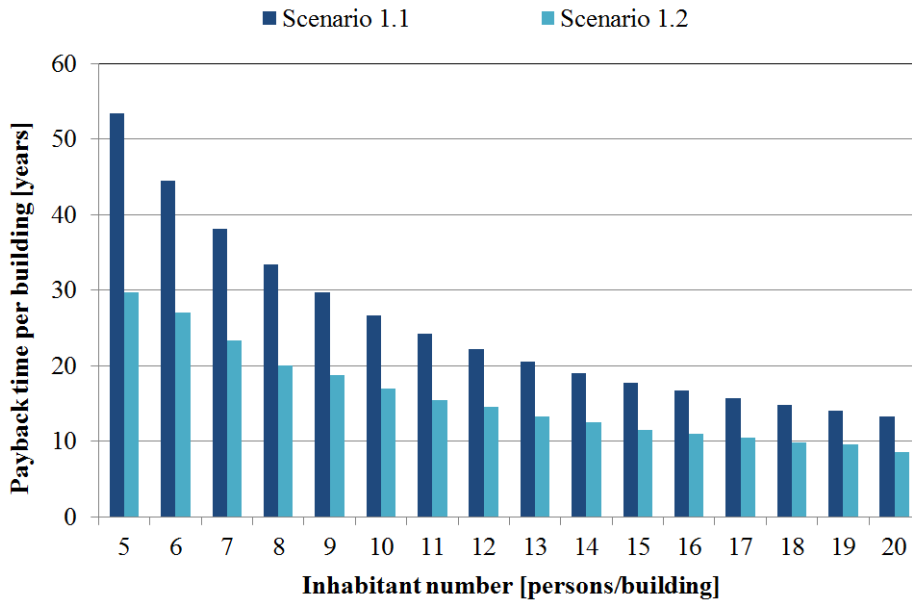
Figure 3.13: Average payback time for five households buildings

considered energy price, which is three times higher than the price used in the present case study. On the other hand, the payback time of 13 years obtained here for a four inhabitant single family building is in the same order of magnitude than the 17 years of Tanha et al. [212], who used a similar energy price.

With the considered investment costs and actual natural gas price, shower or grey water heat recovery are currently not an economically viable solution in buildings with low inhabitant numbers. Subsidies from the state or the municipality would therefore be necessary as incentive for the implementation of such energy saving solutions.

Assessment at city level The yearly total heating demand of the residential sector of Esch-sur-Alzette amounts to 189.2 GWh, of which 23.8 GWh is for domestic hot water demand. By aggregating the energy saving and cost results of the various residential buildings to the level of the city, the absolute and relative savings, investment costs, subsidies necessary to reach a payback time of 10 years (the acceptance limit for the implementation of environmental technologies (Leidl and Lubitz [118])), and the specific cost per saved kWh of energy are determined for the reference year 2015 (Tab. 3.5). The values in brackets are the percentages of subsidies related to the investment costs. With the 2015 natural gas price, subsidies of approximately 60% of the investment costs are required to reach a payback time of 10 years by the inhabitants.

The city energy savings of 3.1% are in line with Deng et al. [46], who estimated the savings of shower heat recovery systems in the city of Amsterdam to be 4%. The relative energy savings of 24.3% in scenario 1.1 come close to the 35% estimated by Leidl and Lubitz [118], considering

Table 3.5: Scenario 1.1 and 1.2 energy savings at city scale, considering 2015 energy price

Scenario	Energy savings [GWh]	Energy savings, related to total heating demand [%]	Energy savings, related to DHW demand [%]	Investment costs [€]	Subsidies to reach 10 years payback time [€]	Specific costs per saved energy [€/kWh]
1.1	5.8	3.1%	24.3%	6'269'018	3'559'414 (57%)	1.08
1.2	12.0	6.3%	50.6%	14'239'324	8'771'601 (62%)	1.19

that they assumed the application of a vertical shower heat exchanger, which yields a higher energy savings than the horizontal HE used in this work.

The geoallocated energy savings per district are represented for the two scenarios in Fig. 3.14a and b.

(a) Scenario 1.1: horizontal shower heat recovery

(b) Scenario 1.2: grey water heat recovery
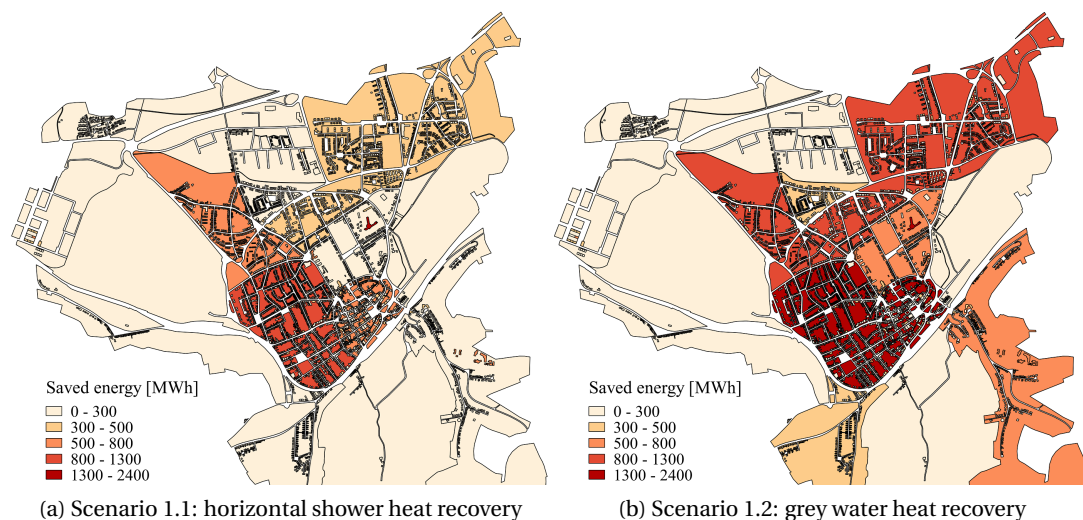
Figure 3.14: Energy savings per districts

3.3.3 Energy optimisation of high efficiency residential buildings

3.3.3.1 Specific input data

Four scenarios focusing on the energy savings in low energy and passive single and multifamily buildings in Luxembourg are considered in this second case study. The reference scenario

2.0 includes space heating and hot water demand at 55°C. The same streams are used for scenario 2.1, to which the shower waste water stream for heat recovery with an horizontal heat exchanger, is added. In scenario 2.2, space heating at 28/35°C and hot water streams at 55°C and all grey water streams listed in Tab. 3.3 are used as inputs. Scenario 2.3 presents an integrated approach to heating optimisation. Space heating remains identical, while DHW is characterised as 45°C hot water (Meggers et al. [139]) and the waste water streams can be cooled down further than 10°C. These streams are used as input to the pinch analysis to design the optimal heat recovery and utility system. It is important to note that in this case, due to the low temperature level, it is assumed that the hot water storage and distribution systems are equipped with an adequat protection against the proliferation of Legionella (e.g. regular thermal desinfection), as indicated in technical standards (Schramek [192], Brand et al. [29]). The energy consumption and investment costs related to this protection are not considered in the following calculations.

The specificities of the considered buildings are summarised in Tab. 3.6. The average inhabitant and household numbers as well as average surface area are taken from the GIS database from Esch-sur-Alzette (Service des travaux municipaux [194]), while the specific space heating energy consumption is from the Luxembourgish legislation on energy efficient buildings (Luxemburgish Parliament [128]). It is assumed that 100% of the households are equipped with a washing machine equipped with an own heating circuit. The space heating nominal load is calculated using the heating signature as described by Girardin et al. [85] and the monthly temperature profile indicated in Luxemburgish Parliament [128] for a theoretical coldest day (-10°C) and average day (7°C), up to an outdoor temperature of 15°C.

The electricity consumption and savings are calculated for three specific periods: winter, intermediate and summer (Tab. 3.7). The period durations have been determined by considering the space heating load and energy requirements of Tab. 3.6, assuming a short duration of 10 hours at minimal outdoor temperature. Floor heating temperature is set to 28/35°C. The temperature of the grey water streams to the sewer does not go below 10°C in scenario 2.2. and 4°C (winter), 7°C (intermediate period) and 17°C (summer) for scenario 2.3.

The heating utility considered is a two-stage air/water heat pump. The first stage covers water temperature of 35°C for space heating and hot water preheating, with a condensation temperature T_{cond} of 38°C, and a second stage for hot water (scenarios 2.0, 2.1 and 2.2: 55°C, scenario 2.3: 45°C), with condensing temperatures of 58°C (scenarios 2.0 and 2.1), 60°C (scenario 2.2, considering a dTmin of 5 K for the grey water heat exchanger) and 48°C (scenario 2.3). For scenarios 2.0., 2.1 and 2.2, the evaporation temperature T_{evap} is 3K below outdoor temperature. For scenario 2.3, the remaining heat going to the sewer is used as partial heat source for the evaporation side of the heat pump (see Tab. 3.7 for the considered temperature levels). The remaining heat source for evaporation is air. Finally, the coefficient of power COP, to calculate the electricity consumption, is obtained with Eq. 3.13, considering an exergy efficiency rate η of 34% (Girardin et al. [85]).

Table 3.6: Building characteristics

Building type	Single family building		Multifamily building	
Total surface [m^2]	166		512	
Inhabitant number [inhabitant]	3		12	
Household number [household]	1		5.5	
DHW energy demand [kWh/a]	1'128		4'584	
Efficiency type	Low energy	Passive	Low energy	Passive
Specific SH energy demand [kWh/m^2]	43	22	27	14
Total SH energy demand [kWh]	7'123	3'644	13'816	7'164
SH maximal load [kW]	3.6	1.8	7.0	3.6
SH intermediate load [kW]	1.2	0.6	2.2	1.2

Table 3.7: Operating period characteristics

Period	Winter	Intermediate	Summer
Duration [hrs]	10	6'163	2'587
Average outdoor temp. [°C]	-10	7	17
Scenario 2.3 evaporation temp. [°C]	4	10	17

$$COP = \eta \times \frac{T_{cond}}{T_{cond} - T_{evap}} \qquad (3.13)$$

3.3.3.2 Energy integration considering WWHR

By applying energy integration design rules based on pinch analysis (no heat exchangers across the pinch point, heat pumps must have their evaporation and condensation elements below and above the pinch point (Becker [11])) to detect optimal heat recovery and utility design configuration, the energy consumption for the optimised scenario 2.3 is calculated. The hot and cold composite curves of the energy integration for the single family, low-energy building are represented in Fig. 3.15 for the three periods. The horizontal segments of the hot stream curves represent the condensation loads of the heat pump. The horizontal segment of the cold streams is the evaporation load. The pinch point, for the four building types, is

situated at 29.5°C for the winter and intermediate periods, and 33.5°C for the summer period. Heat recovery must therefore be designed with two heat exchangers: one to preheat the cold streams with the hot streams below and one for heat transfer between the streams above the pinch point.
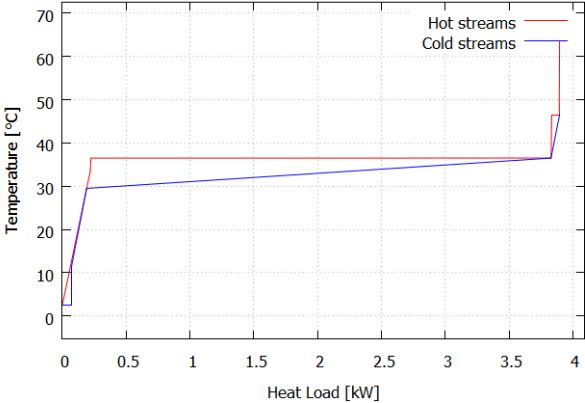
(a) Winter
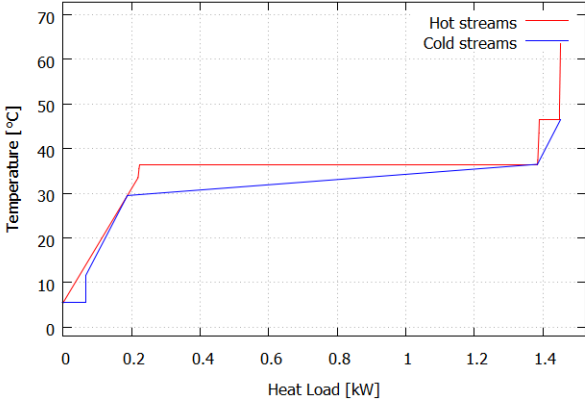
(b) Intermediate
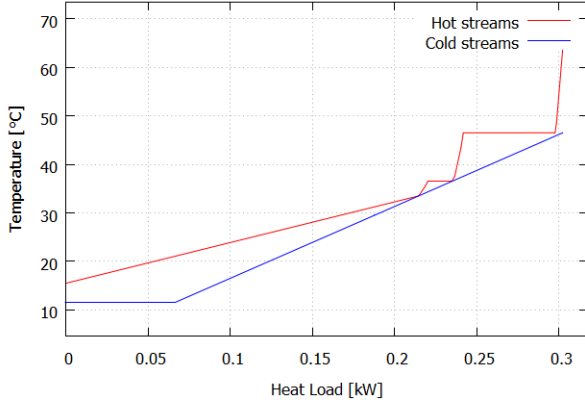
(c) Summer

Figure 3.15: Scenario 2.3 - Pinch analysis diagram

The heat recovery potential in winter is rather limited (4% of the total power) due to the relevance of the space heating requirements. However, the waste heat can be fully used for hot water preheating until a temperature of 11.5°C, then valorised as heat source for the heat pump. During the intermediate period, the grey water is led to the heat pump at a corrected temperature of 14°C, with waste heat recovery contributing to 11% of the load. In summer, where no space heating demand occurs, 55% of the heating load is covered by heat recovery, with the grey water cooled down to 21°C before being used by the heat pump. Due to the small load, using the remaining grey water as heat source for the heat pump reduces the electricity consumption only by 1-2%.

3.3.3.3 Results

The results of the various scenarios of case study 2 are summarised in Fig. 3.16. The percentages indicate the electricity savings related to the electrical consumption for heating.
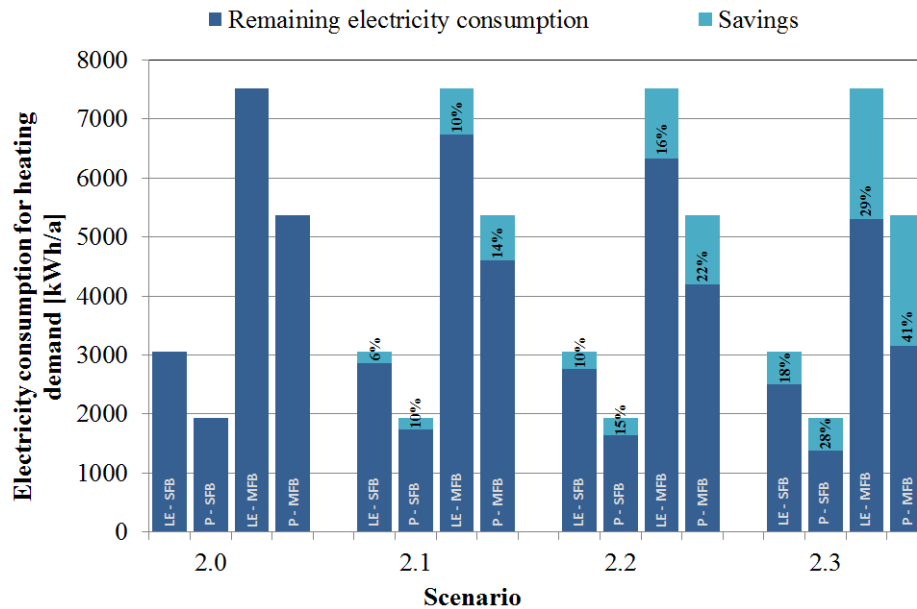
Figure 3.16: Case study 2: results (LE - low energy, P - passive, SFB – single family building, MFB – multifamily building)

With the implementation of a horizontal shower heat exchanger, the total electricity consumption related to heating can be reduced between 6 and 14% according to the building type. The single family building would save 191 kWh/a, while 772 kWh/a would be avoided in the multifamily building. This corresponds to a reduction of 25% of DHW-related electricity consumption. The difference with the savings of 402 kWh/a indicated in Section 3.2.2.1 are due to the heat pump, which produces 2.1 units of heat per unit of electricity for the conditions cited above. The impact of grey water heat recovery on electricity consumption is between 10 and 22%. This represents savings of 38% on the DHW energy requirements with reductions of 291 kWh/a and 1'179 kWh/a for the single family house and the multifamily building, respectively.

Finally, the integrated approach, where hot water production, heat recovery and utility design are optimised, reduces the electricity consumption between 18 and 41%. The single family building would save 544 kWh/a and the multifamily building would reduce its electricity use by 2'213 kWh/a. As already observed in the first case study, waste water heat recovery systems have a larger impact in multifamily buildings than in single family houses.

Considering these outcomes, the implementation of grey water heat recovery systems should be included in an energy integration approach to further optimise the energy savings. Moreover, it is demonstrated that energy integration approaches for high efficiency residential buildings (as deployed by e.g. Fazlollahi et al. [73], Jennings et al. [106] and applied in scenario 2.3) should also include waste water streams and hot water demand optimisation to increase the energy optimisation potential.

3.4 Discussion

A new, detailed method to assess the energy savings and costs at an urban scale from in-building grey water heat recovery in residential buildings is proposed.

One of the main strengths of the deployed work is the detailed characterisation and spatial allocation of residential grey water streams as to mass flow and temperature level, as a function of inhabitant and household numbers. This characterisation allows a more precise assessment of WWHR potential at urban scale. In addition, WWHR energy savings can be related to buildings specificities, e.g. end-use occurrence, building type, age and energy efficiency. Their impact can therefore be calculated in reference to the total heating demand, thus supporting decision processes as to the selection and design of appropriate energy saving measures in buildings. Furthermore, the energy savings and costs are attributed to each specific building in the considered geographical scope. Results can easily be generated at specific spatial levels (building blocks, streets, districts city). The outcomes of urban energy assessments considering WWHR are thus improved, as the large-scale results are obtained by data aggregation. Finally, it is also demonstrated that an integrated approach to heating system selection and design must include hot water demand and grey water streams to further optimise energy consumption.

One limitation of the exposed work consists in the low availability and poor technical, geographical and socio-economic detail level of the input data. Knowledge of the occurrence of retrofitting constraints, which influences configuration selection at the urban level, is also limited. The proposed calculation methods are also simplified to accommodate the problem of scale and do not reflect thermal losses by distribution, energy requirements of desinfection processes related to low temperature solutions (protection against Legionella proliferation), transient conditions of storage systems, or a long-term efficiency drop of the heat exchangers, which further reduce the energy saving potential. Moreover, the urban assessment of case study 1 and the integrated solution deployed in case study 2 do not include other systems (e.g. sewer heat recovery, solar thermal collectors), which could, potentially, further improve the optimisation potential.

Concerning data availability, mass flow and temperature data as a function of building type and socio-economic level of the household must be further gathered. The use of geographically weighted regression would also improve the quality of the assessment as the spatial allocation of certain end-uses would better reflect socio-economic conditions. Also, sensitivity analysis shall be applied to the proposed method in order to quantify the uncertainty of the outcomes, as reflected in case study 1 by the comparison of the payback time values. In addition, the occurrence rate of the implementation constraints, as a function of building type, must be better characterised in order to improve the assessment of WWHR systems at an urban scale. More detailed calculation methods must also be developed for the considered urban scale, although resolution time might become an issue when assessing very large systems. Finally, the competition between in-building and sewer heat recovery configurations must be assessed at an urban scale in order to select adequate solutions according to district/city age and infrastructure.

The main significances of the present work are the characterisation method of grey water streams and the detailed energy saving and cost assessments methods, considering building specificities and various grey water streams, of residential WWHR potential at the urban scale. The exposed methods lead to several contributions in the field of building and urban energy analysis and optimisation.

At building level, residential grey water streams are more specifically characterised by reflecting DHW end-use occurrence as well as inhabitant and household numbers. The assessment for grey water heat recovery potential is therefore qualitatively improved, independently of the configuration (in-building, in-sewer or at waste water treatment plants), which allows a better comparison with other energy saving measures. In addition, the integrated optimal selection of heating utility configurations is extended with the characterisation of the grey water streams as additional source for heat recovery or heat pumps.

At the urban scale, energy and cost assessments at building block, district or city levels are qualitatively improved and spatially better differentiated, as the outcomes are generated by results aggregation of the single buildings. Energy assessments and optimisation, focusing so far mostly on thermal insulation and heating utility selection, are also expanded to include detailed grey water heat recovery as additional optimisation measure.

With the proposed calculation and the related waste water streams characterisation methods, consulting companies conducting urban, municipal or even national energy assessments can increase the scope of their work and better rank and select optimisation scenarios. This will result in a improved decision-making process by local and national politicians regarding the implementation of energy saving measures in the residential sector.

4 Optimised regional waste heat valorisation

Abbreviations and symbols

Abbreviations

CHP	combined heat and power
DHW	domestic hot water
EAF	electric arc furnace
ESCo	energy service company
HP	heat pump
ICE	internal combustion engine
IPPC	integrated pollution and prevention control
MILP	mixed integer linear programming
MINLP	mixed integer non linear programming
WH	waste heat

Continuous variables

C^e	annualised investment cost of equipments e (turbine, heat exchangers, pipelines and heating utility) [€/a]
$C_{ij}^{HE_i}, C_{ij}^{HE_j}$	annualised investment cost of heat exchanger at source i and sink j of connection ij [€/a]
C_j^{HU}	annualised investment cost for hot utility at sink j [€/a]
C_i^{Inv}	annualised investment costs of electricity production at source i [€/a]
C_{ij}^{Inv}	annualised investment costs of heat supply at sink j [€/a]
$C_{i,k,t}^{Op}$	operating costs of electricity production at source i in temperature interval k and period t [€/h]
$C_{j,k,t}^{Op}$	operating costs of heat supply at sink j in temperature interval k and period t [€/h]
C_{ij}^{Pip}	annualised investment cost of transport pipes of connection ij [€/a]

Continuous variables

I_i^{Turb}	turbine investment cost at source i [€]
$I_{ij}^{HE_i}, I_{ij}^{HE_j}$	heat exchanger investment cost at source i and sink j for connection ij [€]
I_j^{HU}	heating utility investment cost at sink j [€]
I^e	investment cost at source i or sink j of equipment e (turbine, heat exchangers, pipelines and heating utility) [€]
I_{ij}^{Pip}	pipe investment cost for connection ij [€]
$\dot{m}_{ij}$	highest mass flow of connection ij [kg/s]
$\dot{m}_{ij,k,t}$	mass flow of connection ij in temperature interval k and period t [kg/s]
P_i	profits from electricity production at source i [€/a]
P_j	profits from heat supply at electricity production at sink j [€/a]
$\dot{q}_{ij,k,t}^{Loss}$	specific heat losses of connection ij in temperature interval k and period t [kW/m]
$\dot{Q}_j^{Bo}, \dot{Q}_j^{CHP}, \dot{Q}_j^{HP}$	highest thermal load of boiler, CHP and heat pumps of sink j [kW]
$\dot{Q}_{j,k,t}^{Bo}, \dot{Q}_{j,k,t}^{CHP}, \dot{Q}_{j,k,t}^{HP}$	thermal load of boiler, CHP unit and heat pump of sink j in temperature interval k and period t [kW]
$\dot{Q}_{i,k,t}^{CU}$	waste heat load transferred to cooling utility of source i in temperature interval k and period t [kW]
$\dot{Q}_{i,k,t}^{Elec}$	thermal load for electricity production at source i in temperature interval k and period t [kW]
$\dot{Q}_{ij}^{HE_i}, \dot{Q}_{ij}^{HE_j}$	heat exchanger loads at source i and sink j for connection ij [kW]
$\dot{Q}_{j,k,t}^{HU}$	hot utility load of sink j in temperature interval k and period t, as the sum of $\dot{Q}_{j,k,t}^{HU,dem}$ and $\dot{Q}_{j,k,t}^{HU,loss}$ [kW]
$\dot{Q}_{ij,k,t}^{HU,dem}$	hot utility load for the demand of sink j in temperature interval k and period t [kW]

Continuous variables

$\dot{Q}_{ij,k,t}^{HU,loss}$	hot utility load for the compensation of the transportation losses of connection ij in temperature interval k and period t [kW]
$\dot{Q}_{ij,k,t}^{Loss}$	heat load of transportation losses of connection ij in temperature interval k and period t [kW]
$\dot{Q}_{ij,k,t}^{WH}$	waste heat load for heat demand and heat losses compensation from source i for sink j in temperature interval k and period t [kW]
$\dot{Q}_{ij,k,t}^{WH,dem}$	waste heat load for heat demand transferred from source i for sink j in temperature interval k and period t [kW]
$\dot{Q}_{ij,k-1,t}^{WH,loss} \dot{Q}_{ij,k,t}^{WH,loss}$	waste heat load for heat losses compensation related to heat transport from source i for sink j at period t from temperature interval $k-1$ to k [kW]
$R_{i,k,t}^{Elec}$	electricity production revenues at source i in temperature interval k and period t [€]
$R_{j,k,t}^{Elec}$	electricity production revenues from utility at sink j in temperature interval k and period t [€]
$R_{i,k-1,t}, R_{i,k,t}$	heat cascaded from interval $k-1$ to the interval below [kW]

Binary variables

$y_{ij,dn}^{Pip,invest}$	use of pipe type with standard size dn of connection ij, for investment cost calculations
$y_{ij,dn,k,t}^{Pip,loss}$	use of pipe type with standard size dn of connection ij in temperature interval k and period t, for heat loss calculations
$y_j^{Bo}, y_j^{CHP}, y_j^{HP}$	existence of heating utility technology, either boiler, CHP or heat pump at sink j

Parameters

$cp_{i,t}, cp_{j,t}$	heat capacity of hot stream i and cold stream j at period t [J/kg*K]
d_{ij}	distance between source i and sink j [m]

Parameters

d_t	duration of period t [h]
$f_{j,t}^{CHP}$	electricity conversion factor of CHP of sink j at period t [-]
f_{ij}^{ground}	underground type for connection ij [open field: 0, road: 1]
$H_{i,t}^{In}$, $H_{j,t}^{In}$,	inlet enthalpy of hot stream i and cold stream j at period t [J/kg]
$H_{i,t}^{Out}$, $H_{j,t}^{Out}$	outlet enthalpy of hot stream i and cold stream j at period t [J/kg]
I_{ref}^{Turb}, I_{ref}^{HE}	reference investment cost for turbines and heat exchangers [€]
I_j^{Bo}, I_j^{CHP}, I_j^{HP}, I_j^{ICE}	investment cost for boilers, CHP units, heat pumps and internal combustion engine specific to sink j [€]
M	large value [-]
$\dot{m}_{i,t}$, $\dot{m}_{j,t}$	mass flow of hot stream i and cold stream j at period t [kg/s]
$\dot{m}_{dn}^{max}$	maximum mass flow allowed in pipe diameter dn [kg/s]
n^e	expected lifetime of equipment e [a]
p^{ICE}	specific investment price for an internal combustion engine [€/kW$_{elec}$]
$p_{i,t}^{Elec,s}$, $p_{j,t}^{Elec,s}$	electricity selling prices for turbine at source i and CHP at sink j [€/kWh]
$p_{i,t}^{Heat,b}$, $p_{j,t}^{Heat,s}$	heat purchase price from source i and selling price to sink j [€/kWh]
$p_{j,t}^{Gas}$, $p_{j,t}^{Elec,b}$	natural gas and electricity purchase prices of sink j at period t [€/kWh]
p_{dn}^{Field}, p_{dn}^{Road}	specific pipe cost according to pipe type, for fields and roads [€/m]
P^{Elec}	Electric load of an internal combustion engine [kW]
$\dot{q}_{dn,k,t}^{Loss}$	specific heat losses of standardised pipe type [kW/m]
$\dot{Q}_{i,k,t}^{Avail}$	available waste heat load at source i in temperature interval k and period t [kW]
$\dot{Q}_{j,max}^{Dem}$	maximal heat load of sink j for the design of the heating utility [kW]
$\dot{Q}_{j,k,t}^{Dem}$	heat demand of sink j in temperature interval k and period t [kW]
$\dot{Q}_{ref}^{turb}$, $\dot{Q}_{ref}^{HE}$	reference turbine and heat exchanger thermal loads for investment cost calculations [kW]
r	interest rate [-]
r_p, r_{ins}	internal and external, insulated, pipe radius [m]

Parameters

$R^{Heat}_{j,k,t}$ heat supply revenues at sink j in temperature interval k and period t [€]

$T^{In}_{i,t}, T^{In}_{j,t}$ corrected inlet temperature of hot stream i and cold stream j at period t [K]

T^{Out}_{t} outdoor temperature at period t [K]

$T^{Out}_{i,t}, T^{Out}_{j,t}$ corrected outlet temperature of hot stream i and cold stream j at period t [K]

$T^{Up}_{k,t}, T^{Low}_{k,t}$ upper and lower temperature level of temperature interval k at period t [K]

α_1 contingencies correction factor [-]

κ_i thermal conductivity of pipe insulation material [W/m*K]

$\eta^{Bo}_j, \eta^{CHP}_j, \eta^{HP}_j, \eta^{Turb}$ boiler, CHP thermal, heat pump and turbine efficiency [-]

γ cost scaling factor for investment cost calculations [-]

Subscripts

dn   standard pipe diameter

i   hot stream

j   cold stream

k   temperature interval

t   time period

Sets

CS set of cold streams j

DN set of standard pipe types dn

HS set of hot streams i

IT_t set of temperature intervals k in period t

TP set of periods t

4.1 Introduction

In 2012, the European Union emphasized, with the directive on energy efficiency (European Parliament [63]), the necessity to valorise waste heat (WH) from manufacturing, electricity production and waste incineration industries at the regional scale. Project proposals for new or extensions of industrial plants and district heating networks must assess, through cost benefit analysis, opportunities to valorise nearby industrial waste heat sources.

While a real interest for regional waste heat valorisation is expressed by industries and municipalities alike, these actors are often reluctant to engage in the actual planning, investment and management tasks as they are not part of their core business activities (Ammar et al. [5], Brueckner et al. [33], Päivärinne and Lindahl [173]). The involvement of a third party, e.g. an energy service company (ESCo), that would bear the risks of the initial investment and manage the waste heat, is therefore necessary to pursue a realistic WH valorisation project. However, regional waste heat recovery represents a challenging engineering task where multiple aspects need to be considered and the economic viability, in competition with other heating alternatives, must be assured for an ESCo to engage in such an enterprise (Päivärinne and Lindahl [173], Deng et al. [45]).

A large number of publications focused on urban waste heat use (Svensson et al. [210], Sandvall et al. [187], Fujii et al. [82], Xia et al. [241]), particularly assessing the economic viability of such projects (Kim et al. [111], Fang et al. [71], Morandin et al. [143], Eriksson et al. [57], Sandvall et al. [188]). In their network design approach, Haikarainen et al. [93] included standard pipe diameters for the calculation of the investment costs. Due to their scope, these works did not formulate waste heat valorisation methods for higher temperature demands, e.g. electricity production or industrial heat demand, and thus missed potential valorisation opportunities (Ammar et al. [5]). Perry et al. [166], Varbanov and Klemeš [225], Čuček et al. [227], Oh et al. [152] adapted the Pinch Analysis and Total Site Targeting methods, initially developed for industrial processes, to large scale energy systems comprised of industries and buildings. Electricity production and transportation heat losses were not considered, despite the fact that the latter aspect is highly relevant for large scale waste heat valorisation (Stijepovic and Linke [207], Wang et al. [236], Nemet et al. [146]). Tveit et al. [219], Stijepovic and Linke [207], Stijepovic et al. [208], Nemet et al. [146] combined detailed Mixed Integer Linear and Non Linear Programming (MILP, MINLP) approaches for waste heat valorisation applicable to industrial zones and beyond, selecting waste heat connection matches according to temperature levels. In these works, the connection selection was generally formulated as linear problem, while the detailed design of the heat exchange network was formulated as a non-linear problem. Oluleye et al. [153] developed an hierarchy-based method for waste heat on and off-site valorisation. However, these works were not formulated for ESCos and did not consider (with the exception of Oluleye et al. [153]) that sinks can have different energy prices for the same fuel type and time period (Eurostat [69]), which influences the WH valorisation opportunities. In addition, transportation heat losses were calculated without taking into account standard pipe sizes/types, which would have improved the quality of the results.

Finally, the selection of the optimal heating utility technology, necessary as a backup system in case of waste heat supply interruption, was not considered. Integrating optimal heating technology selection to the waste heat valorisation would allow the ESCo to improve their service value (Brady et al. [28]).

The objective of this work is to propose a multi-period optimisation method for regional waste heat valorisation and utility selection formulated for ESCos. Potential connections and thermal loads (including heat losses) between industrial and urban systems as well as to electricity production units, considering specific energy prices, are determined according to temperature matches and generated profits. Due to the high number of variables, the method, based on the works of Papoulias and Grossmann [160], Maréchal [133], Mian et al. [141], is formulated as an MILP problem to obtain a single, global, solution (Hillier and Lieberman [98], Lin et al. [120]).

Considering the methodological shortcomings identified in the literature, the proposed work contributes to existing developments with a novel ESCo-specific formulation targeting regional waste heat valorisation. By considering specific sink energy prices in addition to the thermal constraints obtained from the heat cascade, the competition of waste heat valorisation with other energy sources is more thoroughly assessed. With the combined optimal waste heat valorisation and heating technology selection, regional heat valorisation is conducted using an integrated systems approach. Finally, by including standard pipe sizes in the method, the calculation of the heat losses accounts for more realistic constraints on valorisation viability which are often overlooked.

The optimisation problem is formulated in Section 4.2. Its application to the south-west region of the Grand-Duchy of Luxembourg, composed of two steel plants as heat sources as well as three industries and nine towns as heat sinks, is demonstrated in Section 4.3 and Appendix C. The advantages, shortcomings and impacts are discussed in Section 4.4.

4.2 Method

4.2.1 Scope

Similar to the waste heat recovery method for industrial zones of Stijepovic and Linke [207], Stijepovic et al. [208], the design of regional waste heat valorisation system can be decomposed into several steps (Fig. 4.1).

The first step consists of acquiring and processing the necessary data describing the waste heat sources and sinks: heat loads, temperature levels, availability over time, geographical position, energy prices, etc. Several publications focused on the issue of data generation (Persson and Werner [170], Brueckner et al. [33], Forman et al. [78], Persson and Münster [169]), while Grönkvist and Sandberg [87], Chertow [40], Upham and Jones [222], Päivärinne
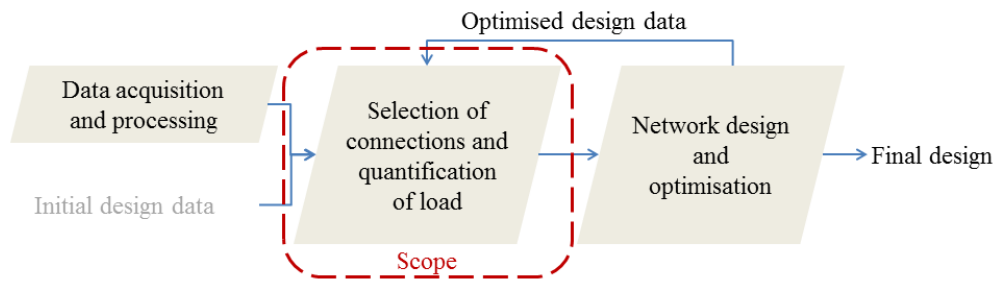
Figure 4.1: Global waste heat valorisation method

and Lindahl [173] assessed operational and financial barriers limiting the valorisation of waste heat. The second step consists of detecting relevant potential connections between source and sink and quantifying the transferable waste heat load, taking into account temperature level matches, heat losses over distance, availability over time, and investment costs. The third step consists of designing the network, which normally leads to a non-linear problem formulation (Stijepovic et al. [208]). In particular, the heat exchanger network should be optimised from a thermo-economic point of view, taking into account the trade-offs between number of exchangers, heat exchange area and operating costs, as has been shown by the sequential approach for multi-period heat exchanger network synthesis (Floudas et al. [76], Mian et al. [141]). Additionally, the transportation network layout should be optimised by combining common network segments (Wang et al. [236]), thus reducing the pipe investment costs. The outcomes of the network optimisation are then used to replace the initial design data of the previous step. The network design is finalised once the results of the second step cannot be further improved.

The scope of the present work focuses on the second step described above, with the selection of profitable connections between hot sources i and cold sinks j and the quantification of the transferred heat load between them. The mathematical model is subdivided into two main parts. First, the economic constraints covering the calculation of profits, revenues, as well as investment and operating costs are given in Section 4.2.2. Second, the technical constraints describing the energy cascade, the energy loss and the energy balance calculations used as input for the investment and operating costs are indicated in Section 4.2.3.

Due to the important decrease in physical strength of common materials for operating temperatures above 400°C (Turton et al. [218]), the application of the method is constrained to streams below this temperature level. This limitation is also applied in the energy auditing tool EINSTEIN (Brunner et al. [34]). Higher temperatures would imply more exotic (and therefore more expensive) materials, which must be specifically accounted for in the economic viability assessment. The method also focuses on the selection of waste heat transportation and not distribution networks, as the latter are independent of the initial heat source. Finally, it is assumed that electricity production from waste heat occurs on the source site.

To ease the equation readability, parameters are in normal font, while dependent and inde-

pendent variables are represented in *italics*. In terms of sets, hot streams i representing industrial waste heat to be valorised are included in the set HS, while cold streams j are in the set CS. As the proposed method is formulated as a multi-period problem, the time periods t are included in the set TP. IT_t represents the set of intervals of temperature k necessary for the heat cascade formulation, which are dependent of period t. Finally, the set DN regroups the pipes of standard diameter dn.

4.2.2 Economic constraints

4.2.2.1 Objective function and global economic constraints

The objective function maximises the annual profits obtained from electricity production P_i at source i, and from the supply of heat and electricity production from the utility P_j of sink j (Eq. 4.1).

$$max \sum_{i \in HS} P_i + \sum_{j \in CS} P_j \tag{4.1}$$

Profits at source i are generated from the difference between revenues from the electricity production with a turbine $R_{i,k,t}^{Elec}$, the combined operating costs $C_{i,k,t}^{Op}$ at each temperature interval k and period t and the annualised investment cost C_i^{Inv} (Eq. 4.2). The definition of the temperature intervals is given in the work of Papoulias and Grossmann [160].

$$P_i = \sum_{t=1,...TP} \sum_{k \in IT_t} (R_{i,k,t}^{Elec} - C_{i,k,t}^{Op}) - C_i^{Inv} \qquad \forall\ i \in HS \tag{4.2}$$

The annual profit P_j of a sink j is obtained from the heat supply and electricity production revenues $R_{j,k,t}^{Heat}$ and $R_{j,k,t}^{Elec}$, operating costs $C_{j,k,t}^{Op}$ of each temperature intervals k and period t and the annualised investment costs C_{ij}^{Inv} related to the connection between source i and sink j (Eq. 4.3).

$$P_j = \sum_{t=1,...TP} \sum_{k \in IT_t} (R_{j,k,t}^{Heat} + R_{j,k,t}^{Elec} - C_{j,k,t}^{Op}) - \sum_{i \in HS} C_{ij}^{Inv} \qquad \forall\ j \in CS \tag{4.3}$$

4.2.2.2 Revenues

In case waste heat is used for electricity generation, assumed here to be implemented at source i, the electricity revenues $R_{i,k,t}^{Elec}$ are determined from the related waste heat load $\dot{Q}_{i,k,t}^{Elec}$ obtained from the heat load distribution (Section 4.2.3), the turbine efficiency η^{Turb}, the duration d_t of period t and the electricity selling price $p_{i,t}^{Elec,s}$ specific for this type of valorisation (Eq. 4.4).

$$R_{i,k,t}^{Elec} = \dot{Q}_{i,k,t}^{Elec} * \eta^{\text{Turb}} * d_t * p_{i,t}^{\text{Elec,s}} \qquad \forall \ j \in CS, \ k \in IT, \ t = 1,...TP \qquad (4.4)$$

The heat supply revenues $R_{j,k,t}^{\text{Heat}}$ are obtained from the heat demand $\dot{Q}_{j,k,t}^{\text{Dem}}$ for the duration d_t considering a heat selling price $p_{j,t}^{\text{Heat}}$ specific to sink j (Eq. 4.5). These revenues are considered as independent of the primary energy form and are therefore expressed as parameter.

$$R_{j,k,t}^{\text{Heat}} = \dot{Q}_{j,k,t}^{\text{Dem}} * d_t * p_{j,t}^{\text{Heat,s}} \qquad \forall \ j \in CS, \ k \in IT, \ t = 1,...TP \qquad (4.5)$$

Finally, as the heating utility selection can also include combined heat and power (CHP) plants, it is also necessary to include the electricity production revenues $R_{j,k,t}^{Elec}$. In addition to the duration d_t and electricity price $p_{j,t}^{\text{Elec,s}}$, these revenues depend on the utility thermal capacity $\dot{Q}_{j,k,t}^{CHP}$. Finally, the electricity conversion factor $f_{j,t}^{\text{CHP}}$ calculating the electrical load based on $\dot{Q}_{j,k,t}^{CHP}$ specific to period t is also included, as CHP plants are composed of an internal combustion engine (ICE) producing electricity during base load and a natural gas boiler for peak loads (Eq. 4.6).

$$R_{j,k,t}^{Elec} = \dot{Q}_{j,k,t}^{CHP} * d_t * p_{j,t}^{\text{Elec,s}} * f_{j,t}^{\text{CHP}} \qquad \forall \ j \in CS, \ k \in IT, \ t = 1,...TP \qquad (4.6)$$

4.2.2.3 Operating costs

The operating costs $C_{i,k,t}^{Op}$ of electricity production at source i is proportional to the valorised waste heat load $\dot{Q}_{i,k,t}^{Elec}$, the heat purchase price $p_{i,t}^{\text{Heat,b}}$ and the duration d_t of t (Eq. 4.7).

$$C_{i,k,t}^{Op} = \dot{Q}_{i,k,t}^{Elec} * p_{i,t}^{\text{Heat,b}} * d_t \qquad \forall \ i \in HS, \ k \in IT, \ t = 1,...TP \qquad (4.7)$$

The operating costs $C_{j,k,t}^{Op}$ at j (Eq. 4.8) include the energy costs of transferred waste heat load $\dot{Q}_{ij,k,t}^{WH}$ (the sum of waste heat load for heat demand $\dot{Q}_{ij,k,t}^{WH,dem}$ and waste heat load for loss compensation $\dot{Q}_{ij,k,t}^{WH,loss}$, Eq. 4.9) from the various sources i in temperature intervals k and the according waste heat source price $p_{i,t}^{\text{Heat}}$ in period t. The operating cost also includes the fuel costs obtained from the loads of the boiler $\dot{Q}_{j,k,t}^{Bo}$, cogeneration unit $\dot{Q}_{j,k,t}^{CHP}$ and heat pump (HP) $\dot{Q}_{j,k,t}^{HP}$, identical to the heating utility variable $\dot{Q}_{j,k,t}^{HU}$ generated from the energy balance described in Section 4.2.3 (Eq. 4.31), multiplied with the energy prices $p_{j,t}^{\text{Gas}}$ and $p_{j,t}^{\text{Elec,b}}$, the according efficiency rate η_j^{Bo}, η_j^{CHP} and η_j^{HP} as well as the duration d_t.

$$C_{j,k,t}^{Op} = [\sum_{i \in H_k} (\dot{Q}_{ij,k,t}^{WH} * p_{i,t}^{\text{Heat,b}}) + (\dot{Q}_{j,k,t}^{Bo} * \eta_j^{\text{Bo}} * p_{j,t}^{\text{Gas}}) + (\dot{Q}_{j,k,t}^{HP} * \eta_j^{\text{HP}} * p_{j,t}^{\text{Elec,b}})] * d_t$$

$$\forall \ i \in HS, \ j \in CS, \ k \in IT, \ t = 1,...TP \qquad (4.8)$$

$$\dot{Q}_{ij,k,t}^{WH} = \dot{Q}_{ij,k,t}^{WH,dem} + \dot{Q}_{ij,k,t}^{WH,loss} \qquad \forall\ i \in HS,\ j \in CS,\ k \in IT,\ t = 1,...TP \qquad (4.9)$$

4.2.2.4 Investment costs

As profitability is calculated on an annual basis, the investment cost I_j^e of equipment e must be annualised to be comparable to the revenues and operational costs, considering the expected equipment lifetime n^e and the annualisation interest rate r (Eq. 4.10). Considering contingencies due to unforeseen circumstances, a correction factor α_1, usually 18% (Turton et al. [218]), is also included.

$$C^e = I^e * \frac{r(1+r)^{n^e}}{(1+r)^{n^e} - 1} * (1 + \alpha_1) \qquad \forall\ e = HE_i,\ HE_j,\ Pip,\ HU \qquad (4.10)$$

The annualised investment costs C_i^{Inv} for electricity production at source i are only related to the acquisition of a turbine, while the costs C_j^{Inv} for sink j are composed of the acquisition costs $C_{ij}^{HE_i}$ and $C_{ij}^{HE_j}$ of the two heat exchangers at i and j, the transportation pipe cost C_{ij}^{Pip} and the heating utility costs C_j^{HU} (Eq. 4.11).

$$C_j^{Inv} = C_{ij}^{HE_i} + C_{ij}^{HE_j} + C_{ij}^{Pip} + C_j^{HU} \qquad \forall\ i \in HS,\ j \in CS \qquad (4.11)$$

Turbine investment costs   The turbine investment costs should be calculated proportionally to the sum of the waste heat load supplied for electricity production $\dot{Q}_{i,k,t}^{Elec}$. As described by Turton et al. [218], the relation is not directly linear to a reference value I_{ref}^{he}, but depends also on a capacity exponent γ (typical value between 0.6 and 0.8). Maintaining linearity for this problem requires treating this non-linear equation using piecewise linearisation as described by e.g. Söderman and Ahtila [193].

$$I_{i_H}^{Turb} = I_{ref}^{turb} * \left(\frac{\sum_{t=1,...TP} \sum_{k \in IT_t} \dot{Q}_{i,k,t}^{Elec}}{\dot{Q}_{ref}^{turb}} \right)^{\gamma} \qquad \forall\ i \in HS \qquad (4.12)$$

Heat exchanger investment costs   The investment costs $I_{ij}^{HE_i}$ and $I_{ij}^{HE_j}$ of the heat exchangers of i and j for the connection ij should be calculated as a function of the heat exchanger area (Turton et al. [218]). However, this would lead to a non-linear problem, as the area is obtained from the division of the load by the logarithmic mean temperature difference, which are both variables. The detailed design of the heat transfer network (especially the thermo-economic optimisation of the heat exchanger area), and therefore the final calculation of the investment

costs, is out of scope of the present method. Therefore, it is proposed to estimate the investment costs $I_{ij}^{HE_i}$ and $I_{ij}^{HE_j}$ as a function of the highest load $\dot{Q}_{ij}^{HE_i}$ and $\dot{Q}_{ij}^{HE_j}$ obtained from the energy balance constraints, reference investment cost $I_{\text{ref}}^{\text{HE}}$ and load $\dot{Q}_{\text{ref}}^{\text{HE}}$ with the same minimum temperature difference value assumed in the heat cascade constraints, and the capacity exponent γ (Eq. 4.13 for heat exchanger in i). This expression can then be piece-wise linearised, as demonstrated for the case study in Appendix B.4.

$$I_{ij}^{HE_i} = I_{\text{ref}}^{\text{HE}} * \left(\frac{\dot{Q}_{ij}^{HE_i}}{\dot{Q}_{\text{ref}}^{\text{HE}}} \right)^{\gamma} \qquad \forall\, i \in HS,\ j \in CS \tag{4.13}$$

Pipe investment costs   The investment costs I_{ij}^{Pip} of the transportation pipes is calculated considering the binary variable $y_{ij,dn}^{Pip,invest}$ for the selection of the adequate pipe diameter, the underground type parameter f_{ij}^{Ground} ($f_{ij}^{\text{Ground}} = 1$ for road, 0 for open fields), the specific pipe costs p_{dn}^{Road} and p_{dn}^{Field} (in €/m) related to standard pipe size and underground type and the distance d_{ij} (Eq. 4.14).

$$I_{ij}^{Pip} = \sum_{dn} (y_{ij,dn}^{Pip,invest} * (f_{ij}^{\text{Ground}} * p_{dn}^{\text{Road}} + (1 - f_{ij}^{\text{Ground}}) * p_{dn}^{\text{Field}})) * d_{ij}$$
$$\forall\, i \in HS,\ j \in CS,\ dn \in DN \tag{4.14}$$

To exclude pipes with insufficient diameter, the binary variable $y_{ij,dn}^{Pip,invest}$ is declared to describe the existence of the connection from i to j of size dn. The existence of the connection of such a size is related to the highest mass flow $\dot{m}_{dn}^{\text{max}}$ allowed in the pipe dn and the highest mass flow $\dot{m}_{ij}$ of connection ij over all periods t as obtained from the heat cascade constraints (Eq. 4.15-4.16).

$$\dot{m}_{ij} \geq \sum_{k \in IT} \dot{m}_{ij,k,t} \qquad \forall\, i \in HS,\ j \in CS,\ t = 1, ... TP \tag{4.15}$$

$$\sum_{dn} y_{ij,dn}^{Pip,invest} * \dot{m}_{dn}^{\text{max}} \geq \dot{m}_{ij} \qquad \forall\, i \in HS,\ j \in CS,\ dn \in DN \tag{4.16}$$

To avoid the selection of more than one diameter, the sum of the binaries $y_{ij,dn}^{Pip}$ cannot exceed one (Eq. 4.17).

$$\sum_{dn} y_{ij,dn}^{Pip,invest} \leq 1 \qquad \forall\, i \in HS,\ j \in CS,\ dn \in DN \tag{4.17}$$

Heating utility investment costs The investment cost I_j^{HU} of the heating utility, currently a natural gas boiler, a heat pump or a CHP unit with peak boiler, is determined according to the binary variables y_j^{Bo}, y_j^{CHP} and $y_{j_C}^{HP}$ selecting the technology type with the investment prices I_j^{Bo}, I_j^{CHP} and I_j^{HP} specific to each sink (Eq. 4.18).

$$I_j^{HU} = y_j^{Bo} * I_j^{Bo} + y_j^{CHP} * I_j^{CHP} + y_j^{HP} * I_j^{HP} \qquad \forall \, j \in CS \qquad (4.18)$$

The investment costs I_j^{Bo}, I_j^{CHP} and I_j^{HP} are input parameters determined by considering the highest load demand $\dot{Q}_{j,max}^{Dem}$. Concerning CHP plants, the investment cost I_j^{CHP} includes the cost of internal combustion engines designed to meet a certain heating base load determined by the user as well as the peak boilers required to reach $\dot{Q}_{j,max}^{Dem}$ (Eq. 4.19).

$$I_j^{CHP} = I_j^{ICE} + I_j^{Bo} \qquad \forall \, j \in CS \qquad (4.19)$$

Existing central heating utilities are reflected by setting the investment costs I_j^{Bo}, I_j^{CHP} and I_j^{HP} to zero.

With Eq. 4.20, only one technology can be selected at one sink.

$$y_j^{Bo} + y_j^{CHP} + y_j^{HP} = 1 \qquad \forall \, j \in CS \qquad (4.20)$$

The relation between these variables and the utility heat loads $\dot{Q}_j^{Bo}$, $\dot{Q}_j^{CHP}$ and $\dot{Q}_j^{HP}$ provided to sink j are defined with M a large value (Eq. 4.21-4.23).

$$\dot{Q}_j^{Bo} - y_j^{Bo} * \mathsf{M} \leq 1 \qquad \forall \, j \in CS \qquad (4.21)$$

$$\dot{Q}_j^{CHP} - y_j^{CHP} * \mathsf{M} \leq 1 \qquad \forall \, j \in CS \qquad (4.22)$$

$$\dot{Q}_j^{HP} - y_j^{HP} * \mathsf{M} \leq 1 \qquad \forall \, j \in CS \qquad (4.23)$$

The utility heat loads $\dot{Q}_j^{Bo}$, $\dot{Q}_j^{CHP}$ and $\dot{Q}_j^{HP}$ are the highest load of all periods t, obtained from the sum of the loads over all temperature intervals k constrained by the operating costs of Eq. 4.8 (Eq. 4.24-4.26).

$$\dot{Q}_j^{Bo} \geq \sum_{k \in IT_t} \dot{Q}_{j,k,t}^{Bo} \qquad \forall \, j \in CS, \, t = 1, \dots TP \qquad (4.24)$$

$$\dot{Q}_j^{CHP} \geq \sum_{k \in IT_t} \dot{Q}_{j,k,t}^{CHP} \qquad \forall\ j \in CS,\ t = 1, \dots TP \qquad (4.25)$$

$$\dot{Q}_j^{HP} \geq \sum_{k \in IT_t} \dot{Q}_{j,k,t}^{HP} \qquad \forall\ j \in CS,\ t = 1, \dots TP \qquad (4.26)$$

4.2.3 Energy constraints

The geoallocated hot and cold streams are characterised by their mass flow rate $\dot{m}_{i,t}$, $\dot{m}_{j,t}$, inlet enthalpy $H_{i,t}^{In}$, $H_{j,t}^{In}$, outlet enthalpy $H_{i,t}^{Out}$, $H_{j,t}^{Out}$, heat capacity $cp_{i,t}$, $cp_{j,t}$, corrected inlet temperature $T_{i,t}^{In}$, $T_{j,t}^{In}$ and corrected outlet temperature $T_{i,t}^{Out}$, $T_{j,t}^{Out}$ for period t. Identically to the pinch analysis method, the temperatures are corrected in order to consider the minimum temperature difference $dTmin$ of the heat exchanger: hot stream temperatures are decreased by $dTmin/2$, while cold stream temperatures are increased by $dTmin/2$.

4.2.3.1 Heat cascade formulation

The energy balance of a source i and a sink j in the temperature intervals k at period t is represented in Fig. 4.2.

For each source i in temperature interval k and period t, the energy balance is composed of the available waste heat load $\dot{Q}_{i,k,t}^{Avail}$, the waste heat cascaded from the interval above $R_{i,k-1,t}$ and to the one below $R_{i,k,t}$, the waste heat valorised for electricity production $\dot{Q}_{i,k,t}^{Elec}$, the load of the cooling utility $\dot{Q}_{i,k,t}^{CU}$, the transferred waste heat $\dot{Q}_{ij,k,t}^{WH,dem}$ for the demand of the various sinks j and finally the transferred waste heat $\dot{Q}_{ij,k,t}^{WH,loss}$ to compensate the temperature decrease related to the losses $\dot{Q}_{ij,k,t}^{Loss}$ of $\dot{Q}_{ij,k+1,t}^{WH,dem}$ (Eq. 4.27).

$$R_{i,k-1,t} + \dot{Q}_{i,k,t}^{Avail} - \sum_{j \in CS}(\dot{Q}_{ij,k,t}^{WH,dem} + \dot{Q}_{ij,k+1,t}^{WH,loss}) - \dot{Q}_{i,k,t}^{Elec} - \dot{Q}_{i,k,t}^{CU} - R_{i,k,t} = 0$$
$$\forall\ i \in HS,\ k \in IT,\ t = 1, \dots TP \qquad (4.27)$$

The heating demand $\dot{Q}_{j,k,t}^{Dem}$ of sink j in temperature interval k and period t is covered by the sum of the transferred waste heat $\dot{Q}_{ij,k,t}^{WH,dem}$ and, in case waste heat is not available or too expensive, the heating utility $\dot{Q}_{j,k,t}^{HU,dem}$ (Eq. 4.28).

$$\dot{Q}_{j,k,t}^{Dem} - \sum_{i \in HS} \dot{Q}_{ij,k,t}^{WH,dem} - \dot{Q}_{j,k,t}^{HU,dem} = 0 \qquad \forall\ j \in CS,\ k \in IT,\ t = 1, \dots TP \qquad (4.28)$$
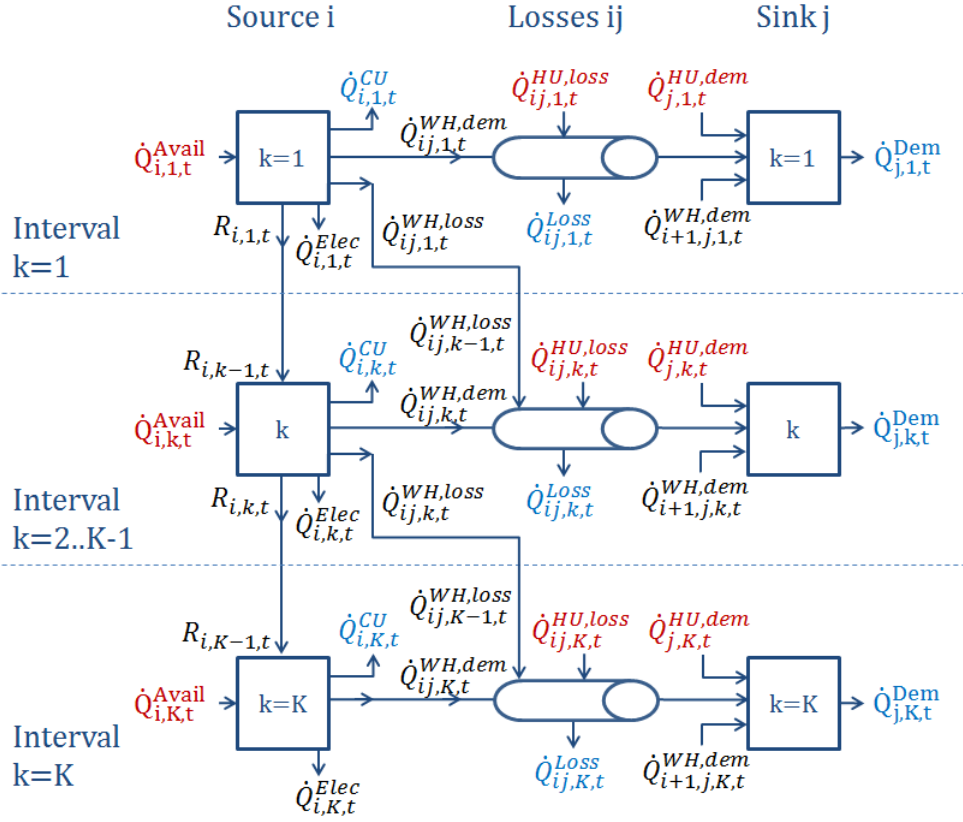
Figure 4.2: Regional heat cascade

The heat losses $\dot{Q}_{ij,k,t}^{Loss}$ of connection ij are compensated by waste heat $\dot{Q}_{ij,k-1,t}^{WH,loss}$ from the temperature interval $k-1$ above, in order to reach the upper temperature level of k, and, if necessary, by the heating utility $\dot{Q}_{ij,k,t}^{HU,loss}$ (Eq. 4.29).

$$\dot{Q}_{ij,k,t}^{Loss} - \dot{Q}_{ij,k-1,t}^{WH,loss} - \dot{Q}_{ij,k,t}^{HU,loss} = 0 \qquad \forall\, i \in HS,\; j \in CS,\; k \in IT,\; t = 1,...TP \qquad (4.29)$$

The selection of the hot utility technology is completed with the sum of the load per technology type, thus making the link with the Equations 4.24-4.26 of the investment costs constraints (Eq. 4.30-4.31).

$$\dot{Q}_{j,k,t}^{HU} = \dot{Q}_{j,k,t}^{HU,dem} + \sum_{i \in HS} \dot{Q}_{ij,k,t}^{HU,loss} \qquad \forall\, j \in CS,\; k \in IT,\; t = 1,...TP \qquad (4.30)$$

$$\dot{Q}_{j,k,t}^{HU} = \dot{Q}_{j,k,t}^{Bo} + \dot{Q}_{j,k,t}^{CHP} + \dot{Q}_{j,k,t}^{HP} \qquad \forall\, j \in CS,\; k \in IT,\; t = 1,...TP \qquad (4.31)$$

4.2.3.2 Heat losses

The heat losses $\dot{Q}_{ij,k,t}^{Loss}$ are calculated as the product of the distance d_{ij} and the specific heat losses per pipe length $\dot{q}_{ij,k,t}^{Loss}$ for connection ij in interval k and period t, thus reflecting the varying outdoor temperature over time (Eq. 4.32).

$$\dot{Q}_{ij,k,t}^{Loss} = \mathsf{d}_{ij} * \dot{q}_{ij,k,t}^{Loss} \qquad \forall\ i \in HS,\ j \in CS,\ k \in IT,\ t = 1,...TP \qquad (4.32)$$

As a consequence of the energy balance formulations of Eq. 4.27 and Eq. 4.29, the heat losses $\dot{q}_{ij,k,t}^{Loss}$ are determined for each temperature interval k instead of considering the final pipe diameter calculated for the investment costs with $y_{ij,dn}^{Pip,invest}$. Therefore, the losses $\dot{q}_{ij,k,t}^{Loss}$ are calculated using a binary variable $y_{ij,dn,k,t}^{Pip,loss}$ selecting the pipe diameter for connection ij in interval k and period t and the specific heat losses $\dot{\mathsf{q}}_{\mathsf{dn,k,t}}^{\mathsf{Loss}}$ for the diameter dn (Eq. 4.33).

$$\dot{q}_{ij,k,t}^{Loss} = \sum_{dn \in DN} (y_{ij,dn,k,t}^{Pip,loss} * \dot{\mathsf{q}}_{\mathsf{dn,k,t}}^{\mathsf{Loss}}) \qquad \forall\ i \in HS,\ j \in CS,\ k \in IT,\ t = 1,...TP \qquad (4.33)$$

The binary variable $y_{ij,dn,k,t}^{Pip,loss}$ must be constrained to exclude diameters where the maximum permitted mass flow $\dot{\mathsf{m}}_{\mathsf{dn}}^{\mathsf{max}}$ is smaller than the actual mass flow $\dot{m}_{ij,k,t}$ of connection ij, in interval k and period t (Eq. 4.34). The smallest of the permitted diameters is automatically selected as it leads to the lowest heat losses and investment costs.

$$\dot{m}_{ij,k,t} \leq \sum_{dn \in DN} (y_{ij,dn,k,t}^{Pip,loss} * \dot{\mathsf{m}}_{\mathsf{dn}}^{\mathsf{max}}) \qquad \forall\ i \in HS,\ j \in CS,\ k \in IT,\ t = 1,...TP \qquad (4.34)$$

To ensure that only one diameter is selected, Eq. 4.33 must be further constrained (Eq. 4.35).

$$\sum_{dn \in DN} y_{ij,dn,k,t}^{Pip,loss} \leq 1 \qquad \forall\ i \in HS,\ j \in CS,\ k \in IT,\ t = 1,...TP \qquad (4.35)$$

The variable mass flow $\dot{m}_{ij,k,t}$ of connection ij is obtained from the transferred waste heat $\dot{Q}_{ij,k,t}^{WH,dem}$ from Eq. 4.27 and Eq. 4.28 as well as the enthalpy or the heat capacity and upper and lower temperatures $\mathsf{T}_{\mathsf{k,t}}^{\mathsf{Up}}, \mathsf{T}_{\mathsf{k,t}}^{\mathsf{Low}}$ of interval k at period t (Eq. 4.36). This approach maintains linearity of the formulation, as the temperature difference of the interval k is a parameter. The use of the actual temperature difference of connection ij aggregated over all temperature intervals k would lead to non-linearity and thus must be treated in this way. The decision to formulate the method as MILP thus implies an overestimation of the heat losses for a connection across several temperature intervals.

$$\dot{m}_{ij,k,t} = \frac{\dot{Q}_{ij,k,t}^{WH,dem}}{cp_{k,t} * (T_{k,t}^{Up} - T_{k,t}^{Low})} \qquad \forall\ i \in HS,\ j \in CS,\ k \in IT,\ t = 1,...TP \qquad (4.36)$$

The parameter $\dot{q}_{dn,k,t}^{Loss}$ is calculated with the equation given by Çomakli et al. [155] (Eq. 4.37). T_t^{Out} is the average outdoor temperature for period t. κ_i is the thermal conductivity of the pipe insulation material (in W/m*K), while r_p and r_{ins} are the internal and external, insulated, pipe radius, respectively.

$$\dot{q}_{dn,k,t}^{Loss} = 2 * \frac{\frac{T_{k,t}^{Up} + T_{k,t}^{Low}}{2} - T_t^{Out}}{\frac{1}{2*\pi*\kappa_i} * \ln(\frac{r_{ins}}{r_p})} \qquad \forall\ dn \in DN,\ k \in IT,\ t = 1,...TP \qquad (4.37)$$

4.3   Case study

The proposed method is applied to the south-western region of the Grand-Duchy of Luxembourg (Western Europe). The case study encompasses two steel production sites as heat sources (star symbol in Fig. 4.3). As potential heat sinks, three industries (triangle symbol) in the sectors of asphalt, hard metals and plastic manufacturing as well as the residential users of the City of Esch-sur-Alzette (second-largest city in the country) and eight nearby towns (circle symbols) are considered, comprising 62'540 inhabitants, an area of 73.5 km^2 and a population density of 851 inhabitants/km^2. For comparison, the metropolitan area of Porto (Portugal) in 2014 had a density of 851 inhabitants/km^2 and the area of Zürich (Switzerland) 865 inhabitants/km^2, while the European average was 117 inhabitants/km^2(Eurostat [68]).

4.3.1   Input data description

4.3.1.1   General data

The case study is built considering energy prices in Luxembourg from 2015. The data is organized in five mutually exclusive periods covering in total 8'760 hours, with t_1= 1hr, t_2= 6'036hrs, t_3= 168hrs, t_4= 2'381hrs and t_5=168hrs. t_1 represents the coldest day of the year, t_2 and t_3 the intermediate period where space heating ($T_t^{out} \leq 15°C$) and domestic hot water (DHW) are required, and t_4 and t_5 the periods where only DHW heating is used by the residential users. Waste heat is available for t_1, t_2 and t_4, while one week production interruptions of the steel plants are assumed in t_3 and t_5. The average outdoor temperatures for the different periods are $T_{t_1} = -7°C$, $T_{t_2,t_3} = 9°C$, $T_{t_4,t_5} = 15°C$. The transportation distance between sources and sinks, within 4 km and thus supposedly viable (Ammar et al. [5]), is obtained with the line measurement tool of QGIS Development Team [178], by manually drawing a connection between the source and the closest building of the considered sink. By overlaying
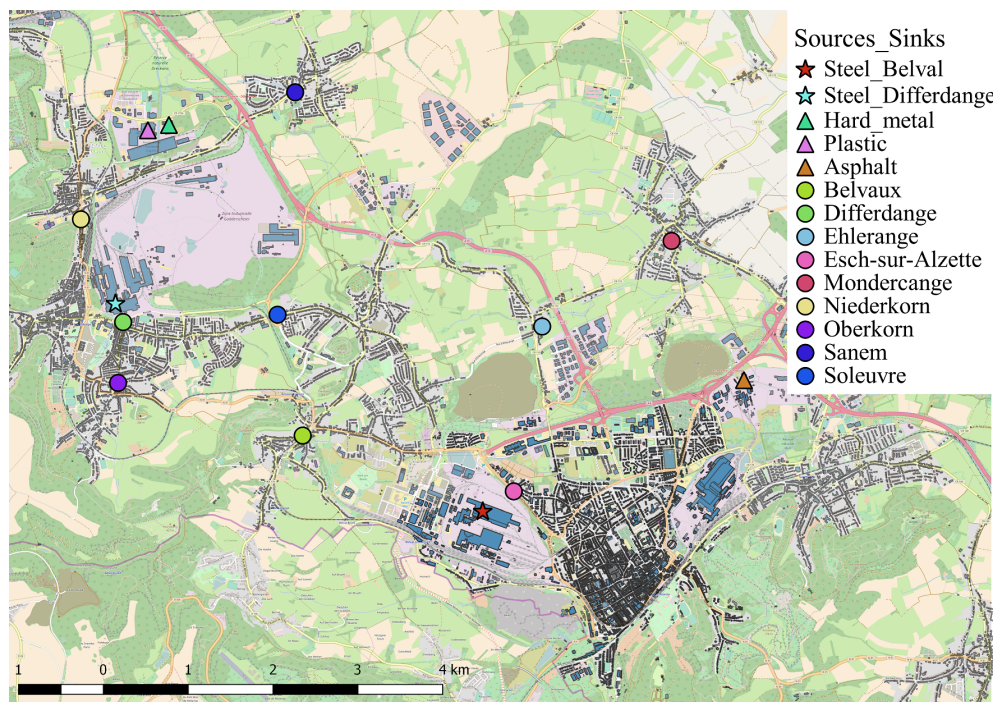
Figure 4.3: Regional waste heat sources and sinks

OpenStreetMap (www.openstreetmap.org) terrain information, data on the ground type (road or field) is obtained (Appendix B.1).

The problem, comprising 64'764 variables, is formulated in AMPL (Fourer et al. [79]) and solved with CPLEX (IBM [102]) on an Intel Core 2 Duo T9400 2.53 GHz Processor and 8 GB RAM.

4.3.1.2 Process data

The hot streams of the steel plant sites, representing an energy quantity of 1'297 GWh/a, are summarised in Tab. 4.1. The selection of the process stream types and the characterisation of their physical properties are based on Tarres-Font [213], who assessed the site of Differdange in detail. The author mentioned that waste heat recovery from the Electric Arc Furnace (EAF) off-gases after post-combustion and from the water jacket is technically difficult due to the dust separation system limiting the formation of dioxin but also constraining the temperature levels of the hot streams. These heat sources are nevertheless considered here, as they present extremely high load and temperature levels, thus potentially generating high enough revenues to justify a modification of the processes. The inlet temperature levels were set to a maximum of 400°C. An initial cooling end temperature of 40°C is considered, to which a dTmin of 10K is applied to obtain a final system temperature of 50°C. The loads of the site of Belval were proportionally adapted as a function of the production mass flow estimated from nominal data of the Integrated Pollution and Prevention Control (IPPC) authorisation, considering a

24 hours, 6 days/week production schedule and a correction factor of 75% to reflect reduced production activity. All sources are assumed to be located at the same place in the plants.

Table 4.1: Heat source data

Site	Stream	Load [kW]	Temp. T_{in} [°C]	Temp. T_{out} [°C]
Steel_ Differdange	EAF off gases after post combustion	43'750	400	50
	EAF off gases end of water jacket	40'625	400	50
	EAF off gases end after quenching	7'500	400	50
	WBF 1 off gases	3'250	400	50
	WBF 2 off gases	4'125	400	50
Steel_Belval	EAF off gases after post combustion	24'306	400	50
	EAF off gases end of water jacket	13'542	400	50
	EAF off gases end after quenching	4'167	400	50
	WBF 1 off gases	1'806	400	50
	WBF 2 off gases	2'292	400	50

The main thermal streams of the three industrial sink sites, totaling 74 GWh/a of energy demand, are described in Tab. 4.2. According to the heat cascade approach, the temperatures were corrected by a temperature difference of 10K to consider the temperature difference from the heat exchanger, except for the streams of the non-ferrous manufacturing plant, which are set to 400°C. The temperatures and specific heat demands are taken from Stadler [198], based on data from Brown et al. [32], Peinado et al. [164] for the asphalt industry, Vlachopoulos and Wagner [232], Wen [238] for the plastic manufacturing industry and Zawrah [243], NIST [149] for the hard metal manufacturing plants. The mass flow data is based on information from the IPPC authorisation of the asphalt plant and estimated as 1'000kg/h and 5'000 kg/h for the two other industries, considering a 12 hours, 5 days/week production schedule.

The residential heating demand data (Tab. 4.3) is generated using the regression analysis information of Bertrand et al. [19], combined with georeferenced data indicating residential building type and location (Entreprise des Postes et Télécommunications [56], Service des travaux municipaux [194]) as well as averaged building age, inhabitant and household number data from the 2011 population census (Statec [199]). The total energy demand amounts to 455 GWh/a. The temperature levels are those of the district heating systems of the city of Luxembourg (70/95°C), to which a correction temperature difference of 10K is added. Non-residential buildings are not included, as the necessary data is not available.

Table 4.2: Industrial heat sink data

Site	Stream	Load [kW]	Temp. T_{in} [°C]	Temp. T_{out} [°C]
Asphalt manufacturing	Aggregate heating	5'079	30.0	185.0
	Evaporation	2'521	109.9	110.1
Plastic manufacturing	Heating	65	30.0	174.9
	Melting	65	174.9	175.1
	Superheating	26	175.1	220.0
Hard metal manufacturing	Oxide reduction heating	417	30.0	400.0
	Carbonisation heating	102	30.0	400.0

Table 4.3: Urban heat sink data

Site	Stream	Load [kW], t_1 / t_2 & t_3 / t_4 & t_5	Temp. T_{in} [°C]	Temp. T_{out} [°C]
Belvaux	Space heating and DHW	23'380 / 7'329 / 503	80	105
Differdange	Space heating and DHW	34'499 / 11'006 / 1'015	80	105
Ehlerange	Space heating and DHW	3'850 / 1'196 / 67	80	105
Esch-sur-Alzette	Space heating and DHW	81'981 / 26'333 / 2'714	80	105
Mondercange	Space heating and DHW	15'072 / 4'688 / 272	80	105
Niederkorn	Space heating and DHW	19'023 / 6'022 / 493	80	105
Oberkorn	Space heating and DHW	12'734 / 4'014 / 305	80	105
Sanem	Space heating and DHW	11'203 / 3'487 / 206	80	105
Soleuvre	Space heating and DHW	21'456 / 6'703 / 430	80	105

The CHP units are composed of an internal combustion engine and a peak boiler. The ICE load corresponds to the sink load at period t_2 and t_3, while the boiler load make up the remaining power demand at t_1. With a thermal efficiency of 47% and an electrical efficiency of 39% (ASUE [7]), the electricity conversion factor $f_{j,t}^{CHP}$ necessary for the revenue calculations of

Eq. 4.6 is set to 26% for t_1 and 83% for the other periods, thus reflecting the use of the ICE as base-load unit producing electricity, while the remaining heating demand is covered by the natural gas boiler. The efficiency of the electricity production turbine on the steel plant sites is considered to reach 24% (Tarres-Font [213]). The boiler is attributed an efficiency of 90%. The efficiency of the heat pumps are calculated considering a Carnot efficiency of 55% (Becker et al. [13]), an average outdoor temperature of -1°C and the uncorrected process temperatures indicated in Tab. 4.2 and Tab. 4.3.

The pipe internal and external diameters, maximum mass flows per size and heat transfer rate k_i (0.0255 W/m*K) are taken from the design manual of a pipe manufacturer (Isoplus [105] - Appendix B.2). To cover the full range of temperature intervals of this case study, the heat transfer fluid considered is Dowtherm A thermal oil, which can be used at temperatures as low as 12°C and up to 425°C which makes it an acceptable fluid for this study. The heat capacity data, given in Appendix B.3, is taken from Dow Chemical Company [50].

The expected lifetime of heating utilities and heat exchangers are assumed to be 15 years and 30 years for the pipes.

4.3.1.3   Economic data

For the annualisation calculation, an interest rate r of 2% is considered (2015 average interest rate for Luxembourgish non financial corporations, www.bcl.lu). Cost data not from 2015 are recalculated for the reference year using the correction indexing factor from the Chemical Engineering Plant Cost Index (http://www.chemengonline.com).

For a 1'090 kW boiler, Buderus [35] indicates a price of 76'668 CHF, excluding VAT (17% in Luxembourg). A 2015 average exchange rate of 0.94 €/CHF is considered. A specific price of 300 €/kW for large heat pumps is taken from Boissavy [26]. Concerning ICEs price, ASUE [7] provided for 2011 a relation between electrical power and specific price in €/kW$_{elec}$ (Eq. 4.38). By multiplying the thermal load of the ICE with the electricity conversion factor $f_{j,t}^{CHP}$, the specific price related to the thermal load at period t is obtained.

$$p^{ICE} = 9'332.6 * (P^{Elec})^{-0.4611} \tag{4.38}$$

The specific pipe costs p_{dn}^{Road} and p_{dn}^{Field}, listed in Appendix B.2, are taken from Nussbaumer and Thalmann [151]. The heat exchanger costs are based on data from Tarres-Font [213] and were recalculated for the assumed minimum temperature difference of dTmin=10K. The curve has been piece-wise linearised in 5 segments, and is represented in Appendix B.4.

Concerning the heat selling price, natural gas prices of 48.50 €/MWh for the domestic sector and 38.19 €/MWh for industrial sinks are assumed (Statec [203]). One of the largest district heating systems indicates that its tariff, which is aligned with the largest heat supplier of the

country, will not be above that of an autonomous heat production (www.sudcal.lu/distribution, in French). The values for natural gas to provide the heat are therefore used as a proxy which would be what sinks would be paying otherwise. The gas price for municipal boiler and CHP plants, 43.36 €/MWh, is an average of residential and industrial gas prices. The electricity purchase price for the heat pumps, 146.75 €/MWh, is an average of residential and industrial prices with an additional 25% for grid costs (Statec [204]). These energy prices have been confirmed by local actors (energy providers and a municipality). The selling price of internal combustion engines is set at 74 €/MWh (Luxemburgish Parliament [127]). Electricity production from waste heat valorisation is not currently addressed by national regulations. The price would have to follow market trends, around 30 €/MWh (http://www.epexspot.com), which is not sufficient to be viable. Considering that this electricity generation would have a lower impact on the environment than the current gas and coal-based production, reduce exergy losses, improve the overall energy efficiency of the region and be provided by a local source, it is therefore argued that it should be considered as a form of renewable energy. As reference, the price for hydroelectric power plants of 125 €/MWh (Luxemburgish Parliament [129]) is used. This is an intermediate price when considering various renewable energy sources (wind, photovoltaic, biomass use, etc.) and it is assumed that the production profile of hydropower and waste heat electricity production are similar in terms of stability and prediction, compared to solar or wind energy.

As raised by Svensson et al. [210] and Morandin et al. [143], the waste heat selling price depends on several factors (e.g. minimal and maximal prices, generated revenues for the source, etc.). Therefore, the optimisation scenarios are considered with values ranging from 0 to 30 €/MWh in steps of 5 €.

4.3.2 Results

4.3.2.1 Regional valorisation considering different waste heat selling prices

The profits generated by the ESCo for the supply of heat from industrial waste heat sources and CHP units as well as from production of electricity, the revenues of the steel manufacturing company, the quantity of valorised waste heat and the produced electricity under various waste heat selling prices are represented in Fig. 4.4.

Given the Luxembourgish context, if the steel plants were to provide their waste heat at no cost, the profits of the ESCo would reach a maximum of 25 M€, with more than 1'000 GWh of waste heat valorised for electricity production (210 GWh) and for the heating demand of all the considered towns (441 GWh). Due to their constant heat demand over the year, it is more economically attractive to install CHP plants for the industrial sinks (additional electricity production of 60 GWh). The same valorisation configuration is obtained with a waste heat price of 5 €/MWh, with the ESCo receiving 20 M€ and the steel plants revenues reaching 5 M€. With a waste heat price above 5 €/MWh, the electricity production by turbine is no more
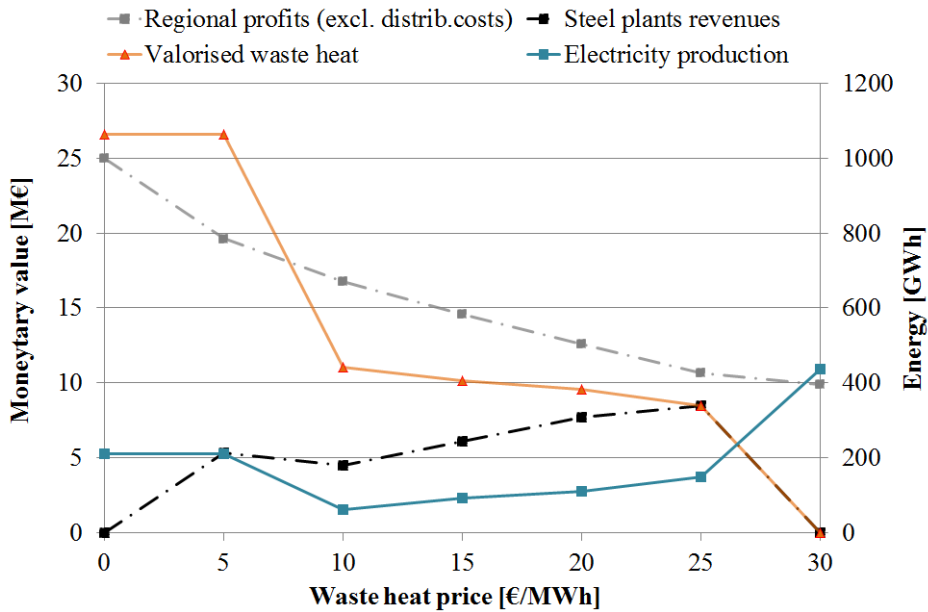
Figure 4.4: Profits, revenues and energy quantities in function of waste heat prices

profitable, an outcome also observed by Tveit et al. [219]. At 10 €/MWh, all towns are still sustained with waste heat, while connections to Ehlerange and Mondercange are not viable at a price above 10 €/MWh, Sanem above a price of 15 €/MWh and Belvaux above a price of 20 €/MWh. The heat demand is then covered by CHP plants, again increasing the electricity production in the region. Natural gas boilers and heat pumps are not retained as heating technology when no WH is valorised.

With a price of 25 €/MWh, and although the steel plants are supplying less heat (338.3 GWh to cover heat demand, 1.4 GWh for the heat losses), their revenues are reaching their maximum at 8.5 M€, while 10.7 M€ would be obtained by the ESCo. These profits are allocated as 70% from waste heat transportation and to 30% from the CHP plants. Above this WH price, CHP plants are economically more viable in this case study and the steel plants would not generate any revenues. The profits of the ESCo would also reach their lowest value with 9.9 M€. Detailed data on revenues, investment costs, payback time, valorised heat and energy losses at this waste heat price is provided in the next section.

4.3.2.2   Regional waste heat valorisation at 25 €/MWh

The resulting waste heat transportation networks and selected utilities, considering a waste heat price of 25 €/MWh, are represented in Fig 4.5.

The total investment costs for heat exchange and transport, the operating costs, the revenues from heat supply and electricity production as well as the payback time are indicated in Tab. 4.4 in detail for the waste heat valorisation sinks and in aggregated form for the remaining
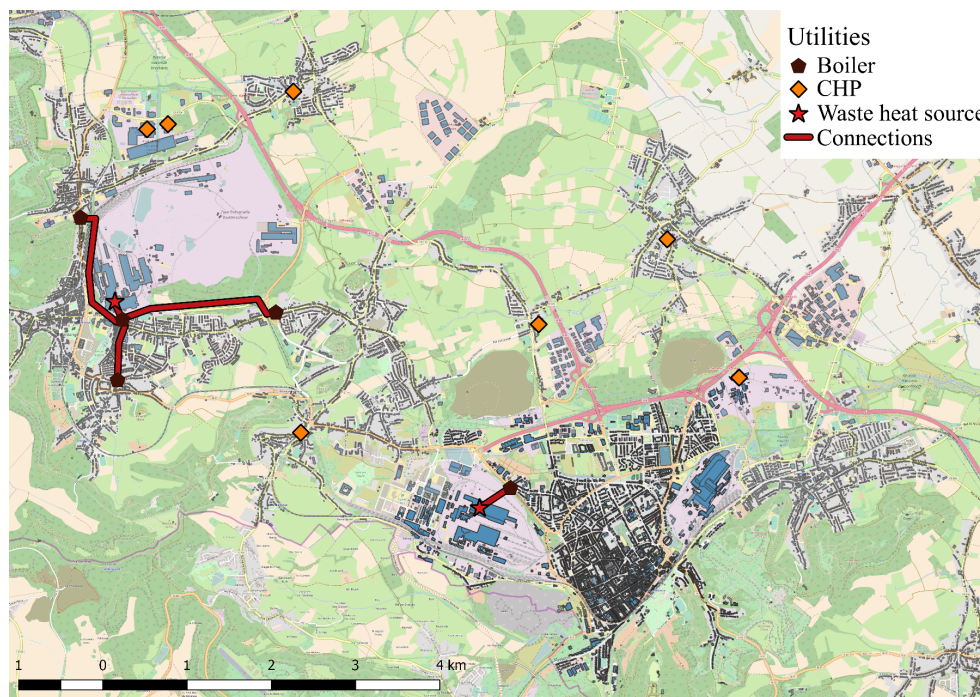
Figure 4.5: Waste heat valorisation and selected utility technologies for a waste heat price of 25 €/MWh

sites. The investment costs for the waste heat valorisation equipments are given in Tab. 4.5. The payback time reaches 3 years for waste heat valorisation in nearby sinks (Differdange, Esch-sur-Alzette), and increases up to 5.6 years for more distant sinks. With an average of 2.4 years, it should be mentioned that, under the prices considered above, the actual payback time of the CHP plants strongly varies according to the amount of heat delivered, with values ranging between 1 and 13 years.

Table 4.4: Revenues and costs

Sink [-]	Total investment costs [M€]	Yearly operating costs [M€/a]	Heat supply revenues [M€/a]	Electricity production revenues [M€/a]	Payback time [a]
Differdange	5.9	1.8	3.8	-	3.0
Esch-sur-Alzette	14.4	4.4	9.2	-	3.0
Niederkorn	4.6	1.0	2.1	-	4.2
Oberkorn	3.9	0.7	1.4	-	5.4
Soleuvre	6.7	1.1	2.3	-	5.6
Sum of sinks with CHPs	9.9	15.7	8.8	11.0	2.4

Table 4.5: Investment costs

Sink [-]	Total investment costs [M€]	Utility [M€]	Pipe [M€]	Heat exchanger at source [M€]	Heat exchanger at sink [M€]
Differdange	5.9	2.5	0.6	1.4	1.4
Esch-sur-Alzette	14.4	6.0	2.3	3.0	3.0
Niederkorn	4.6	1.4	1.4	0.9	0.9
Oberkorn	3.9	1.0	1.6	0.7	0.7
Soleuvre	6.7	1.6	3.2	1.0	1.0

The absolute and relative (transfer to demand ratio, in parenthesis) waste heat loads for time periods t_1, t_2 and t_4, as well as the pipe diameter per connection are given in Tab. 4.6. Instead of selecting the pipe with the largest diameter to cover the highest load demand in t_1, the diameter related to the load of period t_2 is selected to avoid excessive investment costs for the short duration of t_1. Due to the important heat demand, the heat supplied to Esch-sur-Alzette is provided by two different processes, the off-gases after post-combustion and the off-gases of the cooling water jacket.

Table 4.6: Transferred waste heat loads

Sink [-]	Source [-]	Load at t_1 [kW / %]	Load at t_2 [kW / %]	Load at t_4 [kW / %]	Pipe type [-]
Esch-sur-Alzette	Steel_Belval - EAF off gases after post combustion	22'194 (27%)	22'199 (84%)	2'714 (100%)	DN500
	Steel_Belval - EAF off gases end of water jacket	4'130 (5%)	4'134 (16%)	-	DN250
Differdange	Steel_Differdange - EAF off gases end of water jacket	11'004 (32%)	11'006 (100%)	1'015 (100%)	DN400
Niederkorn	Steel_Differdange - EAF off gases end after quenching	6'016 (32%)	6'022 (100%)	493 (100%)	DN300
Oberkorn	Steel_Differdange - EAF off gases after post combustion	4'007 (31%)	4'014 (100%)	305 (100%)	DN250
Soleuvre	Steel_Differdange - EAF off gases after post combustion	6'690 (31%)	6'703 (100%)	430 (100%)	DN300

The transportation heat losses, in absolute value and as percentage of the transferred load, are summarised in Tab. 4.7. They range between 43 and 55 W/m, which is in line with studies on specific pipe losses (Boehm [25]: 60 W/m, Perpar et al. [165]: 49 - 58 W/m). The heat losses are

compensated in this case study by additional waste heat taken from the upper temperature interval and not from the heating utility. The remaining gas consumption, due to the design of the pipe size and the production interruptions in t_3 and t_5 are given in the same table. They amount to 3% of the total energy demand for heating.

Table 4.7: Heat losses

Sink [-]	Source [-]	Load at t_1 [kW]	Load at t_2 [kW]	Load at t_4 [kW]	Remaining gas consumption [MWh]
Esch-sur-Alzette	Steel_Belval - EAF off gases after post combustion	28 (0.1%)	24 (0.1%)	18 (0.7%)	4'936
	Steel_Belval - EAF off gases end of water jacket	23 (0.6%)	19 (0.5%)	-	
Differdange	Steel_Differdange - EAF off gases end of water jacket	13 (0.1%)	11 (0.1%)	8 (0.8%)	2'043
Niederkorn	Steel_Differdange - EAF off gases end after quenching	33 (0.6%)	28 (0.5%)	21 (4.3%)	1'108
Oberkorn	Steel_Differdange - EAF off gases after post combustion	40 (1.0%)	33 (0.8%)	24 (7.8%)	734
Soleuvre	Steel_Differdange - EAF off gases after post combustion	80 (1.2%)	67 (1.0%)	51 (12.0%)	1'213

For this case study, the valorisation of the waste heat does not need further complex network design and optimisation efforts, as the measures are rather straightforward. In the case of waste heat valorisation from the steel plant in Differdange, several optimisation opportunities arise. First, considering the size of the plant, it should be checked with the steel plant manager if one of the sources with a load above 6'022 kW, the heating demand of Niederkorn, is closer to the town than the clustering point assumed. This would allow for a reduction of the pipe costs (20% of the annualised costs). Second, due to the transportation centralised in Differdange, there is the opportunity to use one common heating utility instead of four separate ones. This would further reduce the specific investment costs of the utility (36% of the annualised costs). Finally, the optimisation method selected various processes as heat sources, although either the loads of the EAF off-gases after post-combustion or at the end of the water jacket are sufficiently high to cover the heating demand of the four towns. The costs of the heat exchangers at the source (22% of the annualised costs) would then be reduced. The waste heat valorisation in Esch-sur-Alzette can be improved by joining the two heat sources of the steel plant at the level of the transportation pipes, reducing the pipe investment costs. However, before the detailed network layouts and utility selection is finalised, the design selection should be further discussed with the local actors to ensure the inclusion of potential constraints influencing the layout of the networks (e.g. ease of access of the heat sources)

or additional opportunities (e.g. the existence of service tunnels from the steel plants to the towns).

The low payback times, relevant profits for the ESCo and important revenues for the waste heat transport demonstrate the economic relevance and competitiveness of regional waste heat valorisation for the Luxembourgish domestic sector in 2015, given an adequate heat price. It is also relevant to note that, while 41% of the available waste heat could theoretically be valorised to cover the considered heat demand, only 26% of the excess heat can be economically valorised when constraints of fuel prices, investment costs, energy losses, etc. are included. By considering aspects of economic viability, as well as real population and energy demand densities, this method generates more realistic estimations than other large scale waste heat potential assessments (e.g. Persson and Werner [170]).

4.4   Discussion

A multi-period, MILP-based, method for the optimal regional valorisation of industrial waste heat by ESCos is proposed in this work. It maximises the profits stemming from electricity production and the supply of heat, while considering infrastructure investment and operating costs.

One of the main strengths of the proposed method is the integrated approach to waste heat valorisation. It does not focus solely on the actual WH valorisation, but also includes the possibility of electricity production as well as the optimal selection of the heating utility type necessary as a backup or main heating equipment. Another major contribution is that the formulation allows the consideration of a potential closure of the heat source plant within a few years. Instead of using the typical lifetime of the technical equipment, the lifetime n^e of the annualisation factor of Eq. 4.10 can be used to calculate the investment costs over the prospective remaining lifetime of the plant. Potential investors have the opportunity to assess the annualised investment costs compared to the waste heat price set by the industry, and either require a supply guarantee or a decrease of the waste heat price, thus reducing the investment risk. Finally, while the targeted users are mainly ESCos, potential waste heat supply sites can also use this approach to determine the optimal heat selling price generating the highest revenues. This aspect is of particular importance in case the waste heat valorisation implies changes on manufacturing processes. Normally, industries are resistant to such changes but sufficiently high revenues might prove to be adequate incentive for process modification.

A drawback of the optimisation formulation is that the global heat losses over several temperature intervals k are overestimated, as these are determined independently for each interval. Calculating the losses over all intervals would have led to a non-linear problem, which the authors made efforts to avoid to take advantage of desirable characteristics of MILP formulations (e.g. generation of a global solution). Another current shortcoming is the temperature

limitation to 400°C reflecting material constraints, thus excluding high-temperature waste heat valorisation. This could be avoided by including material type selection as a variable in the problem, although this would further increase its complexity. Finally, the fact that several heat sources or sinks can be situated at the same location is not reflected in the method, although it would potentially reduce utility, heat exchanger and pipe investment costs. This decision is intentional, as the sharing of equipment depends on the temperature level of sources and sinks and mixing of streams cannot be automatically assumed. This issue is, however, solved in the network design and optimisation stage which would be completed in more detail based on the analysis presented here.

The main significance of this work lies in the development of a new method for energy service companies focusing on the optimal valorisation of regional waste heat and the simultaneous selection of the best heating utility technology. The optimisation method expressed here leads to two main contributions in the field of integrated large-scale energy supply networks.

First, a novel waste heat valorisation problem is formulated for ESCos instead of industries or municipalities. The outcomes differ from similar works insofar as the configuration selection is based on highest profitability instead of lowest operating and investment costs. The method also considers that competing sinks can have different energy prices, an aspect rarely considered which, however, influences the selection of the valorisation opportunities.

Second, the method improves regional waste heat valorisation methods by also considering optimal heating technology and standard pipe diameter selection. With this integrated approach, the solutions regarding energy provision proposed by the ESCo are more thoroughly assessed, as potential interactions between these aspects are taken into account simultaneously.

5 Conclusions and future developments

5.1 Conclusions

Considering current scientific shortcomings in the field of waste heat recovery, this thesis focused on the modelling of domestic hot and waste water streams and on the assessment and optimisation of building, urban and regional excess heat valorisation.

First, a method characterising the energy-related parameters of domestic hot water streams (shower, bath, washing up, etc.) in households at building and urban scale, together with the necessary input data, was presented. The DHW energy demand of hotels and nursing homes was also addressed. The proposed model provided precise data on energy consumption and temperature level requirements for each stream at the building level, taking into account the number of inhabitants and households, the end-use occurrence, as well as use frequency and duration, based on data from the water domain. The related energy consumption can be put in relation with the total heating demand of the building and, by data aggregation, of a district, a city or a region. It was shown in a real case study that the global outcomes (e.g. specific hot water demand per capita) were in line with similar works. Furthermore it was confirmed that domestic hot water currently only plays a minor role in terms of energy consumption at urban scale, i.e. 12.3% of the residential heat demand of the city considered in the case study. However, with the construction of near-zero buildings and the improvement of the thermal envelope of existing ones, it was also highlighted that domestic hot water will represent between 30 and 50% of the residential building heating demand in the future.

Considering these findings, measures to improve the energy efficiency related to domestic hot water use must be addressed. Residential waste water streams were therefore characterised based on the method proposed above. Using pinch analysis, six different in-building waste water heat recovery configurations were assessed as to their energy savings. Investment cost calculations were also included in the method. As a demonstration, the proposed characterisation and assessment approaches were deployed to the buildings and districts of the first case study, considering shower and grey water heat recovery systems. With the energy

prices of 2015 leading to payback times generally above 10 years, such solutions are barely economically viable in existing residential buildings in Luxembourg. The heating savings in existing buildings ranged between 1 and 12%, while in high efficiency residential buildings these savings ranged between 6 and 22%. An integrated approach, combining WWHR, hot water temperature optimisation and heat pump deployment, led to much more relevant heating savings ranging between 28 and 41% in high efficiency single family and multifamily buildings, respectively, thus demonstrating the relevance of such a holistic method.

With the detailed domestic hot water demand models addressed above, the related energy demand was calculated to be 17% lower than the results obtained from a surface-related approach. The characterisation and spatial allocation of urban system heat demand data were therefore improved with the proposed DHW characterisation method. This is a relevant step in the decision-taking process for regional waste heat valorisation, as it reduces the risks related to uncertain and incomplete data, particularly when investors, like energy service companies, are concerned. An optimisation method maximising profits and based on a mixed integer linear programming model was proposed for this type of actor. The model took into account the specific energy price of the heat sinks, the distances between sources and potential users, the energy losses due to heat transportation as well as the related investment and operating costs. Due to the integrated approach, the proposed model also included the optimal selection of the backup heating utility. The method was applied to the Southern region of Luxembourg, encompassing the same city considered in the former chapters. First, a sensitivity analysis concerning the impact of the waste heat acquisition price was conducted. The production of electricity proved to be viable for prices below 10 €/MWh, while waste heat could still be valorised for heating demand at prices up to 25 €/MWh. Second, the detailed results of the optimisation at a price of 25 €/MWh were assessed. At that price, profits of more than 10 M€/a from the transport of waste heat and the electricity production of combined heat and power systems were obtained.

The various developments of this thesis lead to several contributions in the field of building, urban and regional heat recovery assessment and optimisation, described in detail in the respective chapters. These contributions are globally summarised as follows:

1. The specific domestic hot water streams characterisation method improves the energy assessment of buildings and urban systems. With a better understanding of the energy and temperature requirements of domestic hot water, energy efficiency objectives will be more easily reached as priorities will be better defined. Risks related to data of poor quality in decision-making processes are also reduced.

2. With the complementary characterisation of residential waste water streams, the energy saving impact of various in-building waste water heat recovery systems on the total heat demand is quantified specifically for the considered building, an aspect not yet fully addressed. With the spatial allocation of data and aggregation of the results, the

impact can also be quantified at district, city or regional scale with a bottom-up approach. The outcomes are thus more precise than with methods proposed so far. The relevance of such solutions can be assessed in relation to other energy saving measures. The decision-making process, both by the building owner or local decision-takers, is therefore improved.

3. The impact of an integrated approach including waste water heat recovery in high energy efficiency buildings in Western Europe is quantified for the first time in a practical case study. With savings ranging between 28 and 41%, the importance of a holistic approach to energy optimisation in buildings considering WWHR is concretely demonstrated.

4. An optimisation method for regional waste heat valorisation is formulated specifically for energy service companies, a point of view so far not considered in regional process integration problems. In particular, the selection of potential heat sinks is not only done by considering constraints of temperature levels, distances and costs, but also as a function of the energy price specific to the sink type. This is an aspect barely considered so far and not yet implemented in a mixed integer linear programming formulation targeting regional waste heat valorisation.

By proposing novel or improved methods related to the valorisation of waste heat, this thesis supports the development of energy efficiency solutions in and across the building, commercial and industrial sectors. These solutions will contribute to address global environmental challenges that are constraining the sustainable development of our society.

5.2 Future developments

With the discussions conducted in the various chapters, several issues and potential developments shall be further addressed in the future.

When considering the characterisation of domestic hot water and waste water streams, country-specific data is still too scarce to apply this approach globally. In the short term, typical data concerning the frequency and duration of use, mass flows, etc. must be further acquired. In parallel, the uncertainty behind these models must be addressed. Considering the proposal for an amendment of the EU directive on energy efficiency ([60]), it can be expected that new and more specific data on domestic hot water will soon be available for European countries. This data will also allow for a better calibration of the proposed domestic hot water models. In the mid-term perspective, considering that spatially allocated data related to socio-economic level and age of inhabitants is expected to be available, the models shall be expanded to include these aspects, thus further improving the outcomes of the related energy demand quantification.

Concerning waste water heat recovery, an interesting prospect is, in the short term, to assess the effect of the combination with user behaviour and single component optimisation. In

addition, in-sewer and waste water treatment plant heat recovery configurations should be included in the urban energy and cost assessment methods in order to compare the advantages and disadvantages of centralised and decentralised waste water heat recovery systems. Considering the large number of potential design parameters and waste water (in-building and sewer) heat recovery configurations, it is also suggested that an integrated optimisation method is, in the mid-term, developed to design optimal heat recovery, storage and heating utility systems.

Finally, the proposed regional waste heat optimisation method could be further improved regarding heat loss calculations. An alternative formulation considering the compensation from a single, optimal, temperature interval should therefore be developed. In that framework, a reconciliation of the binary variables concerning the consideration of standard pipe diameters for the investment cost and heat losses calculations should be targeted. In order to further demonstrate the usefulness of the proposed method, the detailed effect of waste heat selling and electricity production prices on the outcomes should also be analysed in future work. In the mid-term, the method will also be extended to cover further practical aspects usually considered in real projects and so far excluded from this work to limit the complexity of the addressed problem. In particular, the investment and operating costs of distribution network, heat transfer fluid, pump station and maintenance work must be integrated in the model. In order to make a full use of regional excess heat, the problem formulation must be updated to include the possibility of low-temperature heat valorisation combined with heat pumps. This formulation should also be expanded to include in-sewer waste water heat recovery systems. In addition to the classical heat transfer media like steam and thermal oil, more innovative solutions like CO_2 networks must be further included. Also the transportation technology should be expanded to include the possibility to select mobile heat transport systems, e.g. via truck or train, which would allow for further flexibility in the management of RWHV scenarios. On a more practical note, data characterisation methods (including the proposed DHW models) should be combined with the optimisation problem formulation to create a tool for energy service companies aiming to valorise available waste heat at a regional scale.

As long term perspective of this thesis, and in view of the relevance of building energy consumption, the integrated optimisation of domestic hot water demand must be further addressed as it yields an important potential for energy savings, therefore supporting energy efficiency objectives set locally, nationally and globally.

A In-building waste water heat recovery models

A.1 Mass flows and temperature levels for shower heat recovery configurations

Configuration 1

The preheated mass flow $\dot{m}^{ph}$ corresponds to the hot water mass flow $\dot{m}^{HW}$, obtained by considering mass (Eq. A.1) and energy (Eq. A.2) conservation equations, with the temperatures expressed in K (Eq. A.3).

$$\dot{m}_{shower} = \dot{m}^{HW} + \dot{m}^{FW} \tag{A.1}$$

$$T_{shower} \times \dot{m}_{shower} = T^{HW} \times \dot{m}^{HW} + T^{FW} \times \dot{m}^{FW} \tag{A.2}$$

$$\dot{m}^{HW} = \dot{m}_{shower} \times \frac{(T_{shower} - T^{FW})}{(T^{HW} - T^{FW})} \tag{A.3}$$

The preheated fresh water temperature T^{ph} of unbalanced flows must be calculated iteratively based on the fresh water mass flow and using the relations between mass flow, temperature difference and heat transfer coefficient U in W/m^2*K, heat exchanger surface A in m^2 and the logarithmic mean temperature difference dTm, expressed in K (Eq. A.4).

$$\dot{Q}_{HE} = \dot{m}^{FW} \times c_p \times (T^{ph} - T^{FW}) = U \times A \times dTm \tag{A.4}$$

The heat exchanger surface A can be obtained from the manufacturer. It is referred to the literature for the calculation procedure of the logarithmic mean temperature difference dTm and the heat transfer coefficient U (e.g. VDI Gesellschaft [228]), as the detailed description would be out of scope of the current urban-scale work.

Configuration 2

The preheated mass flow of configuration 2 corresponds to the shower mass flow. For balanced flows, the preheated water temperature T^{ph} is obtained from heat exchanger efficiency ε provided by certification institutions, e.g. KIWA in the Netherlands (www.kiwa.nl) or Passivhaus Institut in Germany (www.passiv.de), following Eq. A.5.

$$\varepsilon = \frac{T^{ph} - T^{FW}}{T^{WW} - T^{FW}} \tag{A.5}$$

Configuration 3

Concerning configuration 3, the preheated mass flow corresponds to the fresh water flow, a function of the shower mass flow and the system temperatures (Eq. A.6).

$$\dot{m}^{ph} = \dot{m}_{shower} \times \frac{(T^{HW} - T_{shower})}{(T^{HW} - T^{ph})} \tag{A.6}$$

The preheated water temperature T^{ph} is obtained by subtracting the minimum temperature difference $dTmin$ from the waste water temperature (Eq. A.7).

$$T^{ph} = T^{WW} - dTmin \tag{A.7}$$

A.2 Mass and temperature levels for grey heat recovery configurations

Configuration 4

The hot water mass flow $\dot{m}_e^{HW}$ is proportional to the temperatures of the end-use T_e, hot water T^{HW} and fresh water T^{FW} as well as the end-use mass flow $\dot{m}_e$ (Eq. A.8).

$$\dot{m}_e^{HW} = \dot{m}_e \times \frac{(T_e - T^{FW})}{(T^{HW} - T^{FW})} \tag{A.8}$$

The grey water tank temperature is obtained from the energy conservation equation considering the sum of the products between temperature and mass of the various grey water streams and the tank water mass (Eq. A.9).

$$T^{tank} = \frac{\sum_{GW}(T^{GW} \times m^{GW})}{m^{tank}} \tag{A.9}$$

The grey water thermal power is calculated with the tank energy content potentially rejected at sewer temperature, over a period of one hour (Eq. A.10).

$$\dot{Q}^{tank} = \frac{m^{tank} \times c_p \times (T^{tank} - T^{sewer})}{3600} \tag{A.10}$$

Configuration 5

The thermal load $\dot{Q}_e$ of the various DHW end-uses e is obtained by aggregating the daily energy requirements considering the occupant x_{occ} or household numbers of the building. Eq. A.11 is given as example for the load of DHW end-uses related to occupant use (e.g. showering, bathing).

$$\dot{Q}_e = \frac{\sum_{x_{occ}} (\dot{m}_e \times d_e \times f_e) \times c_p \times (T_e - T^{FW})}{3600} \tag{A.11}$$

Configuration 6

The thermal power of a grey water stream $\dot{Q}^{GW}$ is calculated with Eq. A.12, considering the sewer temperature T^{sewer} as final temperature.

$$\dot{Q}^{GW} = \frac{\sum_{x_{occ}} (\dot{m}^{GW} \times d_e \times f_e) \times c_p \times (T^{GW} - T^{sewer})}{3600} \tag{A.12}$$

B Regional waste heat valorisation input data

B.1 Distances and road ratio

Table B.1: Distances / road ratio

Site	Steel_Differdange [km]/[-]	Steel_Belval [km]/[-]
Asphalt	8.89 / 1.00	4.02 / 0.13
Plastic	4.00 / 0.23	7.66 / 0.80
Hard metal	3.54 / 0.20	7.44 / 0.80
Belvaux	3.15 / 1.00	1.39 / 1.00
Differdange	0.20 / 1.00	4.35 / 0.65
Ehlerange	5.91 / 0.95	2.12 / 0.50
Esch-sur-Alzette	4.95 / 1.00	0.44 / 0.20
Mondercange	8.57 / 1.00	3.66 / 0.50
Niederkorn	0.60 / 1.00	6.25 / 0.50
Oberkorn	0.75 / 1.00	4.81 / 0.90
Sanem	2.38 / 0.25	5.74 / 0.50
Soleuvre	1.44 / 0.50	1.88 / 1.00

B.2 Pipe data

The specific costs for DN300 to DN600 have been extrapolated from smaller diameters using a
linear regression approach (Fig. B.1), with R^2=98.7% for roads (Eq. B.1) and 98.4% for open
fields (Eq. B.2). The initial data is taken from Nussbaumer and Thalmann [151].

$$p = 207.9 + 5.8392 * diameter \tag{B.1}$$

$$p = 139.15 + 5.3625 * diameter \tag{B.2}$$
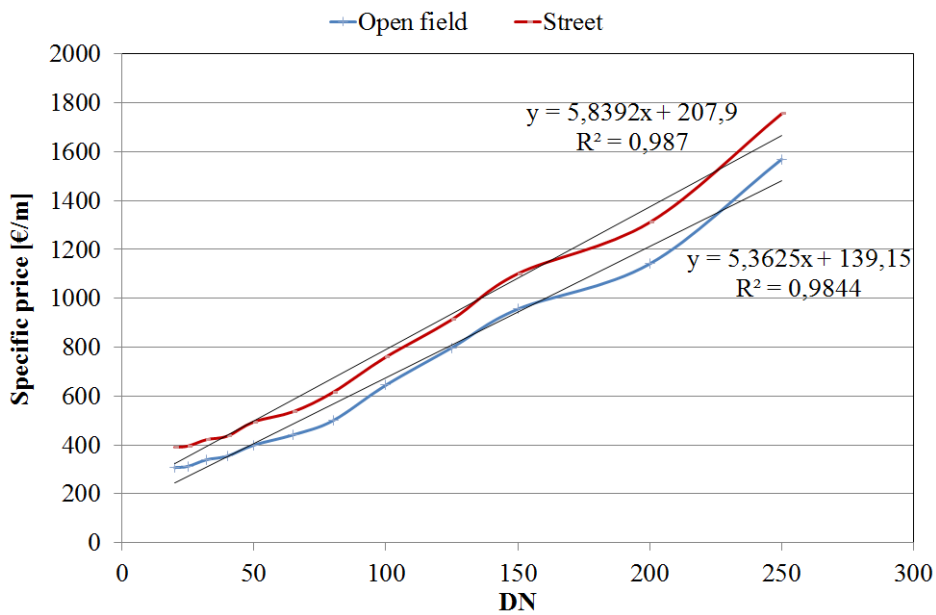
Figure B.1: Linear regression of pipe costs

Table B.2: Pipe data (Isoplus [105],Nussbaumer and Thalmann [151])

Type	Internal radius [m]	External radius, incl. insulation [m]	Maximal mass flow [kg/s]	Cost (road) [€/m]	Cost (open field) [€/m]
DN20	0.014	0.063	0.14	391	308
DN25	0.017	0.063	0.28	396	313
DN32	0.021	0.070	0.56	422	340
DN40	0.024	0.070	0.83	437	355
DN50	0.030	0.080	1.53	495	400
DN60	0.038	0.090	3.06	537	442
DN80	0.045	0.100	4.58	616	500
DN100	0.057	0.125	9.17	760	645
DN125	0.070	0.140	16.11	913	798
DN150	0.084	0.158	26.39	1'101	956
DN200	0.110	0.200	53.61	1'311	1'141
DN250	0.137	0.250	96.67	1'755	1'569
DN300	0.162	0.280	151.94	1'960	1'748
DN350	0.178	0.315	195.83	2'252	2'016
DN400	0.203	0.335	277.78	2'544	2'284
DN450	0.229	0.355	380.56	2'836	2'552
DN500	0.254	0.400	505.56	3'128	2'820
DN600	0.305	0.500	811.11	3'711	3'357

B.3 Heat capacity of transportation fluid

Table B.3: Heat capacity of Dowtherm A (Dow Chemical Company [50])

Temperature interval k	Temperature range [°C]	Heat capacity cp [J/kg*K]
1	400 - 220	2'418
2	220 - 185	2'086
3	185 - 175.1	2'024
4	175.1 - 174.9	2'010
5	174.9 - 120	1'933
6	120 - 110.1	1'842
7	110.1 - 109.9	1'828
8	109.9 - 105	1'821
9	105 - 80	1'779
10	80 - 50	1'701
11	50 - 30	1'630

B.4 Piecewise linearisation of heat exchanger investment costs
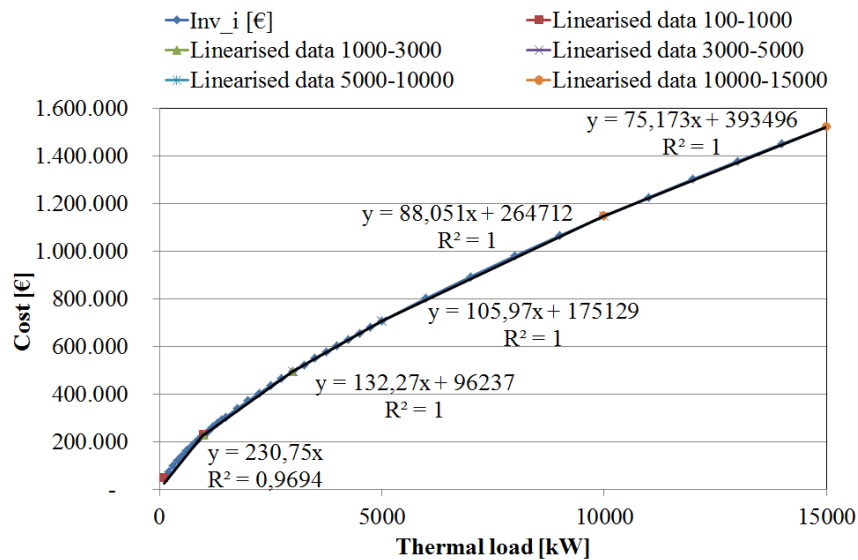
Figure B.2: Piecewise linearisation of heat exchanger costs, based on Tarres-Font [213]

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Bibliography

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Key skills

Scientific and technical skills:

- Integrated material and energy assessment & optimisation
- Database management
- Mathematical optimisation
- Consulting and training in the field of energy
- Project and team management

Language skills: French (native), fluent in written and spoken English, German and Luxemburgish

Software skills: AMPL, Postgres, QGIS, Lyx, MS and Open Office

Professional experience

2017   Luxembourg Institute of Science and Technology, Luxembourg, *Research and technology associate*:

    - R&D in the field of energy efficiency, industrial symbiosis and circular economy,

    - Project definition and management.

2013-2016 Luxembourg Institute of Science and Technology, Luxembourg / Ecole Polytechnique Fédérale de Lausanne, Switzerland, *PhD candidate:*

    - Development of data characterisation, assessment and optimisation methods supporting the valorisation of waste heat at building, city and regional scale (Luxembourgish National Research Fund AFR grant).

2003-2013 Luxembourg Institute of Science and Technology (former Public Research Centre Henri Tudor), Luxembourg, *Senior R&D engineer:*

    - European and national R&D projects in the field of energy assessment methodology development (www.heatmap.lu, www.einstein-energy.net, www.sems-project.eu, www.c2cbizz.com – project manager on SmartHeatFlow, EINSTEIN2, SEMS, C2C-Bizz),

    - Consulting of Luxemburgish ministries and companies in the field of energy assessment, energy optimisation and best available technologies,

- Trainings of process engineers, consultants and students in the field of energy audits and optimisation in industries.

2002-2003 Bureau Goblet Lavandier et associés, Luxembourg, *Engineer:*

- Energy concepts for municipalities in Luxembourg,

- Integrated Pollution Prevention Control (IPPC) authorisation requests for companies.

Education

2004-2011   Degree in mechanical engineering (Dip. Ing. TU), specialisation in energy, Dresden University of Technology, Germany (distance courses, exams with normal students). Main courses: thermodynamics, thermal energy plants, cooling systems, heat exchangers, compressors and pumps. Final thesis topic: exergy assessment of a trigeneration plant in Esch/Alzette (LU)

1997-2001   Degree in electrical engineering (Ing. Ind.), specialisation in energy and system automation, Luxembourg University of applied sciences, Grand-Duchy of Luxembourg. Main courses: electrical energy, electricity distribution, system automation, electrical motors. Final thesis topic: energy concept of 7 municipalities in Luxembourg

Recent publications

2017   A. Bertrand, R. Aggoune, and F. Maréchal. In-building waste water heat recovery: an urban-scale method for the characterisation of water streams and the assessment of energy savings and costs. Applied Energy, 192:110 – 125, 2017. http://www.sciencedirect.com/science/article/pii/S0306261917301137.

A. Bertrand, A. Mastrucci, N. Schüler, R. Aggoune, and F. Maréchal. Characterisation of domestic hot water end-uses for integrated urban thermal energy assessment and optimisation. Applied Energy, 186, Part 2:152 – 166, 2017. http://www.sciencedirect.com/science/article/pii/S030626191630263X.

2016   A. Bertrand, R. Aggoune, and F. Maréchal. In-building waste water recovery: an urban scale method for energy saving assessments. In 29th international conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS), Portoroz, Slovenia, June 19-23 2016.

2015   N. Schüler, A. Mastrucci, A. Bertrand, J. Page, and F. Maréchal. Heat demand estimation for different building types at regional scale considering building

parameters and urban topography. Energy Procedia, 78:3403 – 3409, 2015. http://www.sciencedirect.com/science/article/pii/S187661021502490X.

A. Bertrand, R. Aggoune, and F. Maréchal. Residential and non-residential hot water use models for urban and regional energy integration. In Biennial International Workshop Advances in Energy Studies - Energy and urban systems, Stockholm, Sweden, May 4-7 2015.

Award

Winner of the 2014 Secolux award, supporting research and innovation in the field of construction, for the elaboration of a heat map of Luxembourg on industrial excess heat potential and household heat demand in the framework of the ERDF SmartHeatFlow project.

Personal interests

Member of the local theatre association, cooking, climbing, running, reading, art.