THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Transition pathways for future district heating and cooling systems with thermal energy storage

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Cover:

Roadmaps for energy system transitions identified through the promoting (green) and hindering factors (red)

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Transition pathways for future district heating and cooling systems with thermal energy storage

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Abstract

Buildings’ heating and cooling account for more than 20% of the final energy use within the European countries and are dominated by non-renewable resources. Future district energy systems should enable efficient, fossil-free, and economical energy supply at operating temperatures that end users can directly utilize. This can be achieved by lowering the system temperatures and boosting them on the demand side to increase the overall system efficiency. Ultralow-temperature district heating (ULTDH) and bidirectional fifth-generation district heating and cooling (5GDHC) systems are the solutions. However, the transition of district heating and cooling (DHC) systems from current high-temperature configurations to the future solutions is subject to several uncertainties and challenges, such as energy prices, investment costs, thermal energy storage (TES) distribution, and demand profiles. The variations in these uncertainties were not considered in previous studies. Most of the earlier studies only discussed current perspectives, leaving the future applicability of the DHC system unknown.

Hence, a generalized methodological framework combining energy system optimization with stochastic simulations, uncertainty analysis, and sensitivity assessment is developed in this study to investigate the effects of these uncertainties. Based on a variety of stochastic cases, the index named cost-saving probability (CSP) is utilized to reflect the potential of being economic attractive when comparing the energy systems. The preferred future conditions for different DHC systems are summarized in the roadmaps via proposed key performance indicators (KPIs), indicating a future promising area for DHC design. Meanwhile, the applications and roles of TES in future DHC systems were investigated. Furthermore, combined with the geographical information system-based methodologies and data sources, the proposed KPIs for the entire European building stock were calculated at the hectare level to identify the potential areas of 5GDHC.

The results reveal considerable differences between the systems as different design and operation objectives on least cost and imported electricity are set. The most sensitive factors of the CSP are area demand density, overlapping heating and cooling demand, and linear demand density for the transition to ULTDHC, 5GDHC, and individual systems, respectively. The roadmap also shows the hindering factors for different transitions, as well as the impact of the objective on imported electricity. Besides, the sensitivity analysis results reveal TES’s limited role in integrating variable renewable energy (RE) in high-efficiency DHC systems. In addition, less than 0.1% of the current European building stock has sufficient overlapping heating and cooling demands to efficiently implement 5GDHC. These potential areas are primarily found in city centres involving cooling demands from commercial and industrial processes. While a better energy performance of buildings and warmer climate in the future may decrease the heating and increase the cooling demand, the overlapping part is only slightly increased by around 4%, leading to limited additional application potentials of 5GDHC.

Keywords:

Thermal energy storage; district heating and cooling; uncertainty analysis; bidirectional system; transition roadmap

Teknikvalskarta för framtidens fjärrvärme- och fjärrkylesystem med termisk energilagring

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Sammanfattning

Värme och kyla i byggnader står för mer än 20% av energianvändningen i Europa. Denna domineras av icke-förnyelsebara energikällor. När framtidens energisystem utvecklas ska de möjliggöra effektivare och ekonomiskt hållbar energiöverföring av fossilfri energi vid de systemtemperaturer användarna direkt har nytta av. Detta kan uppnås genom att sänka systemtemperaturen och sedan lokalt höja den på användarsidan i byggnaden. Ultralågtempererade fjärrvärmesystem och dubbelriktade fjärrvärme- och fjärrkylesystem, så kallade femte generationens fjärrvärme- och fjärrkylesystem, bygger på denna princip. För att kunna utveckla dagens högtempererade fjärrvärme- och fjärrkylesystem mot framtidens lösningar måste ett antal osäkerheter och tekniska utmaningar utredas. Bland dessa märks framtida energipriser, investeringskostnader, teknikval, termiska energilagers placering och energibehovsprofiler. Variationen i dessa osäkerheter har inte tagits i beaktande i tidigare studier. De flesta studier diskuterar enbart de nuvarande förutsättningarna vilket ger en oklar bild av vilka faktiska förutsättningar de framtida energisystemen ska optimeras för.

I denna studie utvecklas en generell metodik och ett ramverk som kombinerar optimering av energisystem med stokastiska simuleringar, osäkerhetsanalys och känslighetsanalys. Ramverket syftar till att kunna undersöka effekten av osäkerheterna på vilket energisystem som är optimalt under olika förutsättningar. Utifrån en stokastisk variation av osäkerheterna undersöks den ekonomiska potentialen för de olika energisystemen genom att beräkna prestandakriteriet den sannolika kostnadsbesparingen. De optimala förutsättningarna för olika framtida energisystem summeras i teknikvalskartor där föreslagna prestandakriterier indikerar vilket energisystem som lämpar sig bäst under specifika förutsättningar. Tillämpbarhet och möjligheter med termiska energilager i systemen har undersökts på systemnivå. Slutligen har metoder för geografiska informationssystem kombinerats med dessa datakällor för att beräkna de föreslagna prestandakriterierna för hela Europas byggnadsbestånd. Upplösningen är på hektarnivå och resultaten identifierar potentiella områden för femte generationens fjärrvärme- och fjärrkylesystem.

Resultaten visar att det är stora skillnader mellan vilket system som är mest optimalt utifrån vilka villkor som väljs för lägst kostnad och lägst tillförd elektricitet. De mest känsliga faktorerna för sannolikheten för kostnadsbesparingen är områdets energibehovsdensitet, överlappande värme- och kylbehov samt den linjära energibehovsdensiteten för övergången från lågtempererade fjärrvärmesystem, femte generationens fjärrvärme- och fjärrkylesystem samt individuella värmesystem. Teknikvalskartan visar dessutom att vissa etablerade slutsatser om framtidens energisystem inte gäller när framtidens osäkerheter tas med i analysen. Vidare har termiska värmelager en begränsad roll för att öka andelen variabel förnyelsebar energi i högeffektiva fjärrvärme- och fjärrkylesystem. Resultaten visar också att mindre än 0,1 % av det existerande byggnadsbeståndet i Europa har ett tillräckligt stort överlapp mellan värme- och kylbehov för att möjliggöra effektiv implementering av femte generationens fjärrvärme- och fjärrkylesystem. De mest lämpliga områdena finns framför allt i stadskärnor där det finns ett kylbehov från kommersiella och industriella verksamheter. Slutligen får byggnader allt bättre energiprestanda samtidigt som klimatet blir varmare. Detta leder till ett minskat uppvärmningsbehov men ökat kylbehov. Resultatet visar ett ökat överlapp mellan värme- och kylbehoven med 4 % vilket ger en marginellt större potential för femte generationens fjärrvärme- och fjärrkylesystem.

Nyckelord:

Termiska energilager; fjärrvärme och fjärrkyla, osäkerhetsanalys, dubbelriktat system, teknikvalskarta

List of Publications

This Ph.D. thesis is based mainly on the work presented in the following publications:

I. Zhang, Y., Johansson, P., & Sasic Kalagasidis, A. (2021). Applicability of thermal energy storage in future low-temperature district heating systems – Case study using multi-scenario analysis. *Energy Conversion and Management*, 244, 114518.
II. Zhang, Y., Johansson, P., & Sasic Kalagasidis, A. (2022). Assessment of district heating and cooling systems transition with respect to future changes in demand profiles and renewable energy supplies. *Energy Conversion and Management*, *268*, 116038.
III. Zhang, Y., Johansson, P., & Sasic Kalagasidis, A. (2023). Roadmaps for heating and cooling system transitions seen through uncertainty and sensitivity analysis. Submitted to the journal *Applied Energy*.
IV. Zhang, Y., Johansson, P., & Sasic Kalagasidis, A. (2023). Quantifying overlapped heating and cooling demands and the feasibility of bi-directional systems over Europe. Submitted to the journal *Energy and Buildings*.

Additional Publications

Other publications related to the content of the thesis are listed below:

V. Zhang, Y., Johansson, P., & Sasic Kalagasidis, A. (2022). Feasibilities of utilizing thermal inertia of district heating networks to improve system flexibility. *Applied Thermal Engineering*, *213*, 118813.
VI. Zhang, Y., Johansson, P., & Sasic Kalagasidis, A. (2021). Techno-economic assessment of thermal energy storage technologies for demand-side management in low-temperature individual heating systems. *Energy*, *236*, 121496.

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Yichi Zhang

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Contents

Abbreviations

4GDHC	Fourth-generation district heating and cooling
5GDHC	Fifth-generation district heating and cooling
COP	Coefficient of performance
CSP	Cost-saving probability
DOC	Demand overlap coefficient
DHC	District heating and cooling
DHW	Domestic hot water
EFF/INV	Heating and cooling source performance on unit investment cost
GFA	Gross floor area
GIS	Geographical information system
HPs	Heat pumps
KPIs	Key performance indicators
LCOE	Levelized cost of energy
MC	Monte Carlo
OBJ	Objective
PR	Plot ratio
PV	Photovoltaic
RCP	Representative concentration pathway
RE	Renewable energy
SC	Space cooling
SH	Space heating
TES	Thermal energy storage
ULTDHC	Ultralow-temperature district heating and cooling

Part I

Summary

1 Introduction

This chapter presents the background of the heating and cooling system transitions from current to future scenarios with a large share of renewable energy (RE) production and low carbon emissions. Such transitions are expected to cause challenges and changes in every aspect of the heating and cooling systems. The impacts of future changes are formulated as the aim of this study. Finally, the research framework is presented here.

1.1 Background

Buildings' heating and cooling account for more than 20% of the final energy use within the European Union (EU), of which only 23% is based on RE sources [1]. The European Commission recommended a set of proposals and strategies to achieve the greenhouse gas emission target and reduce the reliance on fossil fuels [2]. Although there is no universal answer to the sustainable transition, the low-temperature district heating, which is often called fourth-generation district heating (4GDH), has been recommended as a robust solution [3].

Driven by the energy-efficient building stock and the synergy between the heating and electricity sectors, 4GDH enables reduced grid losses, the potential integration of waste heat and renewable sources, and higher energy supply efficiency compared to the current district heating (DH) system with a system temperature of 80 °C [4]. A recent guidebook has summarized the economic benefits, practical implementations, obstacles, and challenges of 4GDH, based on more than 100 initiatives and cases [5]. Because of its several full-scale achievements, 4GDH has proven to be a technology-ready option. Conversely, established design traditions and missing links between stakeholders hinder more comprehensive implementation [5].

According to the general concept of low-temperature heating systems, further innovations in DHC systems include ultralow-temperature district heating (ULTDH) and fifth-generation district heating and cooling (5GDHC), as shown in **Figure 1.1**. The ULTDH system has a forward temperature of approximately 35 °C to directly supply space heating (SH). In contrast, decentralized heat pumps (HPs) increase (boost) the network temperature to a required level to meet the domestic hot water (DHW) demand [6]. Deep energy renovations of buildings and low-temperature indoor heating systems, such as floor heating, are prerequisites for the ULTDH system. The lower supply temperature reduces the grid losses and increases the coefficient of performance (COP) of the main central HPs compared to the existing systems [7].

Conversely, the 5GDHC system has an operating temperature close to the annual average of shallow ground (approximately 10 °C–30 °C) to minimize the heat loss from the DHC pipes to the environment [8] and collect the waste heat from cooling processes in buildings. The heating and cooling energy is supplied from the same network using separate local booster HPs and chillers. The entire system is called a bidirectional network [9,10] or a cold district heating network [11]. Generally, the 5GDHC system is more suitable in places with balanced heating and cooling demand. As the cooling demand in European buildings will grow rapidly in the future because of global warming and building renovation projects [12], such waste heat recovery from the cooling process in the 5GDHC system is promising. Numerous studies on 5GDHC can be discovered, as reported in the statistical survey of 40 operating systems [14] and a recent review paper on research gaps and challenges [7]. However, the extent of this transition, particularly, the role of 5GDHC remains unknown.

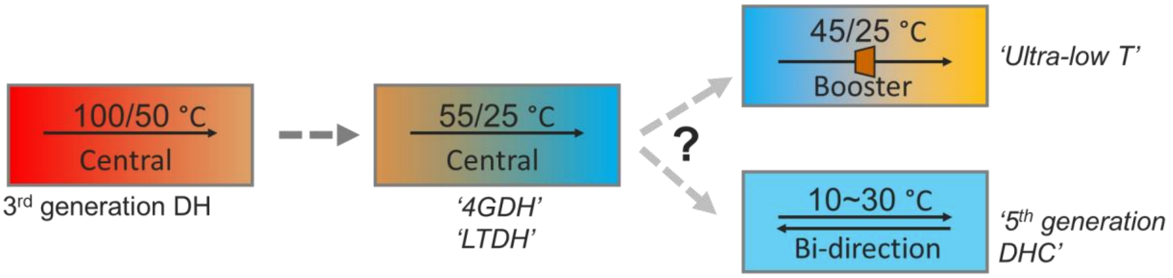


Figure 1.1. Illustrative transitions of the district heating and cooling systems.

Although the transitions of the DHC systems have been discussed in the abovementioned studies, it is common that they were set in the current situations and perspectives. However, several future challenges and changes in energy systems are expected. A summary of these changes is provided in **Table 1.1**. On the supply side, the growing electricity production from variable renewable energy (RE) adds variations and uncertainties to the power grid. The future price levels and variabilities may also differ from the current conditions [13]. On the demand side, the heating and cooling demands will change in the future with the ongoing building renovation projects across Europe and the undeniable global warming [14]. Therefore, this study aims to answer whether the currently planned transition of the DHC system is attractive under future challenges. Furthermore, detailed descriptions of future changes and gaps associated with the DHC system transitions are mentioned in **Chapter 2.2** to prove the relevance of the research question.

Meanwhile, there is a growing need for a flexible operation of the energy system to incorporate more RE. Future costs associated with flexible facilities, such as thermal energy storage (TES), are highly unpredictable. The applications and roles of different TES technologies in the 3GDH and 4GDH systems have been identified in previous studies [15–17]. For the ULTDH and 5GDHC systems with low-temperature ranges and low sensible storage densities, TES sizes have been optimized in the studies only applicable to particular cases [9,18,19]. Corresponding to the research gap in system transitions and future changes, TES applicability under such challenges requires further investigations.

Table 1.1. Overview of challenges and changes in the future energy systems.

Area	Changes
Energy supply	1) Increasing production from centralized renewable energy sources 2) Increasing production from local, household renewable energy units 3) Increasing waste heat from commercial and industrial processes
Energy demand	1) Global warming 2) Building renovation
Regulation	1) Fluctuating primary energy prices 2) Fluctuating electricity prices 3) Growing need for flexible operation 4) Technological development of energy facilities
Stakeholders	1) Different incentives for DHC transitions 2) Different expectations about the renewable energy integrations in DHC

From another perspective, the reported optimal implementations of the novel DHC technologies differ considerably owing to the different applied scenarios [8,20,21]. According to the literature review, research works on DHC planning are commonly placed within limited situations, leaving the general applicability of the DHC transitions uncertain. For example, studies on optimal system design [9,22] are based on cases with balanced heating and cooling demand, which are favorable scenarios for the 5GDHC system. Wirtz et al. [10] identified the key performance indicators (KPIs) of the demand overlap coefficient (DOC) to judge the feasibility of 5GDHC according to demand profiles. In terms of energy prices, a higher electricity price will make the 5GDHC system more economically attractive because the higher operational cost is compensated by its high-efficiency equipment [23]. As it is a relatively new technology, the uncertainties associated with its future investment costs have not been considered in previous studies. Concerning the influence of the system efficiency, although changes in central heating and cooling sources are discussed in previous studies [19,24], changes in the local equipment have not been investigated.

As explained in the previous paragraphs, it is important to consider the possibilities of all parameters to acquire more robust and reliable evidence for the system application, which requires an uncertainty analysis to describe the probability distributions of the desired system performance with respect to the uncertain parameters [25]. Moreover, the specific influences from different uncertain factors and their importance can be evaluated and ranked using the sensitivity analysis method [26]. These analysis methods have been widely applied in distributed energy systems to determine the optimal design [27–29], providing a solid knowledge background for this work. Furthermore, the uncertainties associated with heating and cooling system transitions remain unknown, which is the focus of this work.

1.2 Aims and objectives

Considering the research gaps illustrated previously, the overall goal of this study is to increase the understanding of the transitions of DHC systems under future changes. This study mainly focuses on the applications of TES and their roles in future DHC systems.

A generalized methodological framework is developed, which combines energy system optimization, stochastic simulations, uncertainty analysis, and sensitivity assessment. Parameters from various aspects cover the key uncertainties when planning future DHC system applications. A roadmap that summarizes the preferred and hindering conditions for different transitions is provided. Special focus is paid on the changing roles of TES with energy system transitions. In addition, a set of KPIs is proposed to determine the potential of the 5GDHC system for the existing European building stock.

The current study answers the following questions:

1. How do the different concepts of DHC systems perform under challenges and changes in the future?

2. What are the main sensitive factors that influence the planning of different DHC systems?

3. How large is the application potential of the 5GDHC system in Europe?

4. What is the role of TES technologies in future DHC systems?

Answers to the optimal selection of DHC systems directly affect stakeholders involved in the district energy system design, operation, and use, including energy suppliers, DHC system operators, and end users. From a top-level view, stakeholders, such as urban planners and policymakers, will find the discussion on the sensitive factors meaningful to designing future pathways, giving different perspectives on economic and environmental aspects. Moreover, the methodological framework provides researchers and consultants with a new and integrated way to study future changes and uncertainties.

1.3 Thesis outline

This thesis began with the work on TES units in single-family houses, as reported in the additional **Paper VI** [30]. The applications of water tanks, phase change material (PCM) unit, and building thermal mass in individual heating systems were investigated using bottom-up modeling. The focus was on how these units can act as demand-side management measures to reduce operating costs while increasing RE use. The results revealed significant variations in their performance, as reported in **Paper I** and triggered the idea of creating a roadmap for TES. Besides the individual and traditional 4GDH systems, various innovative DHC options were included in this investigation, as presented in **Chapter 1.1**. Similar to the issues of TES applications, there was no answer on how to plan DHC systems under complex and changing conditions. The idea of a roadmap study was extended to include the DHC field. Furthermore, the flexible usage of DH network inertia as storage media was investigated to expand the choices of TES units, as reported in the additional **Paper V** [31]. The focus of this paper is how the performance of a network storage can be influenced by the applied DHC systems. The results further inspired the discussions on the connections between the TES and DHC systems, which are the main content of **Chapter 5**.

Overall, six studies were included in this thesis. The focus of this thesis is narrowed down to the transitions of DHC systems to present a complete and compact story, as reported in appended **Papers I–IV**. The detailed findings on the applications of network inertia and demand-side TES units from additional **Papers V** and **VI** were omitted in this thesis. However, the multiperspective analysis method and connections with future changes from these papers were the essential inspiration for this thesis.

The outlines of this summary are shown in **Figure 1.2**. Detailed descriptions of the DHC systems and future changes are provided in **Chapter 2** based on the research target and the questions raised in this chapter as proof of the existing research gaps. Subsequently, **Chapter 3** defines the characteristics of future uncertain parameters. The performance of different DHC systems under future changes was analyzed along with the stochastic methods. Additionally, the preferred conditions for planning DHC systems were summarized as different KPIs in the transition roadmap. This part of the thesis is derived from **Papers II** and **III.** Utilizing the results of these papers, the feasible conditions for 5GDHC in the existing European building stock are evaluated in **Chapter 4**, according to the contents in **Paper IV**. Potential areas are assessed geographically, indicating the future role of 5GDHC. Moreover, **Chapter 5** summarizes the roles of TES in the transition of DHC systems based on findings from energy system modeling. This idea is adopted from the TES roadmap study in **Paper I**. It is further improved with the proposed evaluation framework, which can identify the benefits of TES under changing conditions. Finally, the conclusions and recommendations for future research are presented in **Chapter 6**.

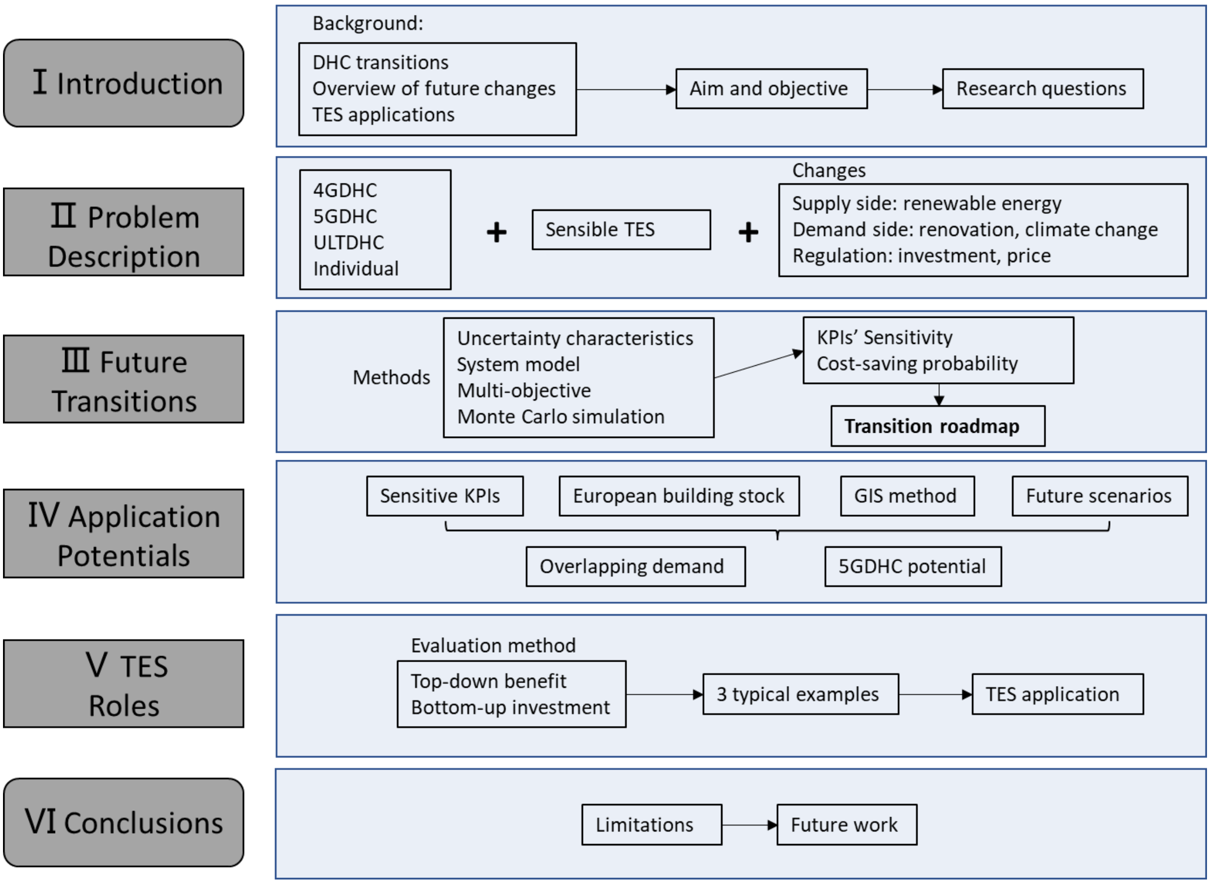


Figure 1.2. Illustrative flowchart of the outline of this thesis.

2 Heating and cooling systems in the future context

This chapter introduces four types of heating and cooling systems, representing the commonly available configuration on the market and innovative system solutions for the future. Various integrations of TES units in these systems are also explained. When moving toward future scenarios, possible challenges and changes from multiple sources on the whole energy system are presented. The state-of-art studies are reviewed to address these issues and clarify the research gaps on the energy system transitions under future challenges.

2.1 Systems descriptions

The typical structures of substations and design temperatures in the 4GDHC, ULTDHC, 5GDHC, and individual systems are presented in **Figure 2.1**. For the individual systems, the air-source HPs and chillers are directly connected to the indoor part. In the four investigated systems, the indoor heating and cooling terminals, such as the floor heating pipes and air-handling units are designed with the same parameters (temperature, flowrate) since the indoor heat and mass transfer process is not the focus of this study.

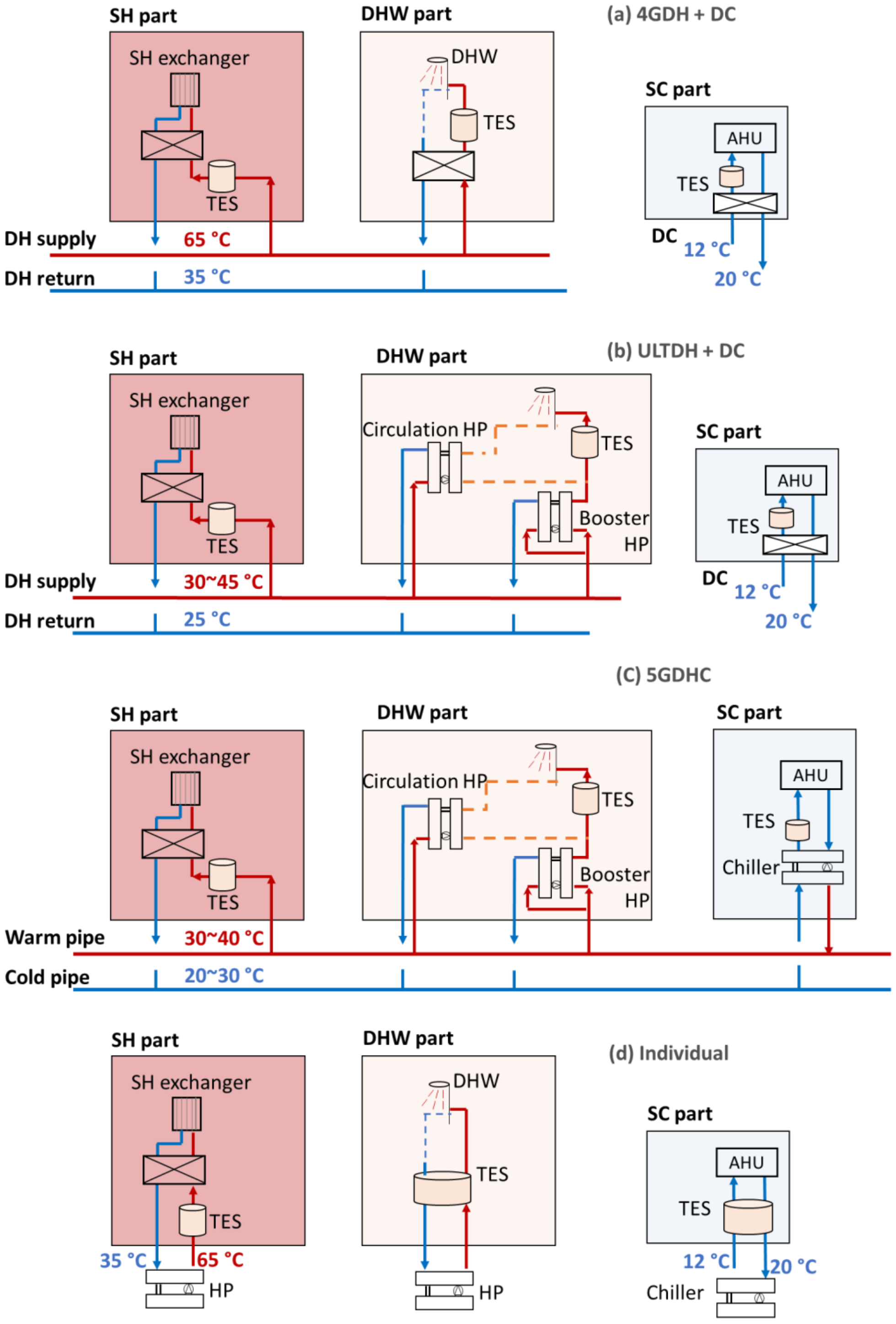


Figure 2.1. Typical structures of substations in the 4GDHC, ULTDHC, 5GDHC, and individual systems.

- 4GDHC: Representation of the initiative toward the low-temperature network [5]. Heating is supplied by the central HP with temperatures of 65 °C/35 °C for the supply and return lines, respectively. The cooling demand is prepared by the city central DC system with a cold water temperature of 12 °C, according to field investigations [32].

- ULTDHC: Combination of ULTDH and DC systems. The supply water temperature from the central HP is reduced to approximately 30 °C–45 °C, which can directly meet the SH demand in buildings (e.g., without conversions in local substations) [33]. To raise the water temperature for DHW demand, water-source booster HPs are installed in the substations [7]. During the low DHW demand period, the water-source circulation HP is activated to cover the circulation heat losses while maintaining the required return temperature by the evaporator. Cooling is supplied by the central DC system, the same as that in the 4GDHC system.

- 5GDHC: Bidirectional looped network with heating and cooling exchange between buildings using warm and cold pipes. The warm pipe temperature is maintained at approximately 30 °C–40 °C, whereas the cold pipe temperature is around 20 °C–30 °C. Besides the booster HPs, water-source chillers are installed on the demand side to prepare the cold water for cooling demand. In turn, the heated water from the condenser is discharged into the warm pipe, which can be used for the heating demand. External sources, including the central HP and compression chiller, are operated to maintain the network at desired temperatures when the heating and cooling demands cannot be internally balanced. This study considered fixed design temperatures for the warm and cold pipes based on dynamic optimization results to simplify the control system [34].

- Individual: Decentralized building-level solution. Air-source HPs with two levels of supply water temperatures are responsible for the space-heating demand and DHW demand separately. Air-source chillers supply cooling. Compared to central solutions, the individual equipment has a broader range of energy efficiencies and investments, which are considered uncertain parameters in **Chapter 3**.

Previous studies and projects have discussed several implementations of the TES units in heating and cooling systems. A generic classification is shown in **Table 2.1**. The location of the TES implies the application scales of the storage unit. The city-level TES unit has a large size of up to 10,000 m^3 and is usually located with a centralized heating and cooling plant. Conversely, the building-level TES unit has a much smaller size and much higher initial investment owing to the scale effect [35]. Regarding applications, TES units can be designed and used in both heating and cooling systems. In the 5GDHC system, as the separate heating and cooling networks are aggregated into one looped system, the TES can be a coordinator to balance the two sectors. Sensible TES is commonly used because of its stable performance and relatively low cost. The central and building-level decentralized water tanks are the most widely adopted storage configurations, as shown in **Table 2.1**. However, the storage density of sensible TES is affected as the operating temperature difference gradually decreases in the heating and cooling systems. There is a growing interest in using latent and thermochemical TES units as efficient and space-saving solutions. The performance of these alternatives is further evaluated and compared in **Chapter 5**.

Although most TES types in **Table 2.1** are applicable in heating and cooling systems, certain combinations, such as the building-level long-term seasonal TES are not feasible due to technical or economic imperfections. Long-term storage is mostly applicable at the city level, but short-term storage is easily achievable across all storage sizes. Four major benefits of TES have been identified and summarized in **Chapter 5**, along with the purpose of using TES. **Chapter 5** explains the detailed analysis of these benefits and provides a generalized evaluation method to simply estimate TES feasibility. The method is tested on typical configurations of TES in heating and cooling systems.

Table 2.1. Classification of TES in heating and cooling systems.

Category	Subdivisions
Location	• City-level central • Community level • Building level
Application	• Cooling system • Heating system (space heating, domestic hot water) • Heating and cooling balance system
Storage media	• Sensible (water, rock, aquifer, building thermal mass) • Latent • Thermochemical
Storage length	• Short-term: hours, up to a day • Middle-term: days, up to a week • Long-term: months
Purpose	• Peak shaving • RE integration • Energy price difference • Balance of multiple sources

2.2 Future changes

Three categories of future changes from the supply side, demand side, and regulations are considered in this thesis, as shown in **Table 1.1**. On the supply side, future variations and uncertainties in electricity prices are mainly caused by the increasing deployment of RE, the probable further phase-out of nuclear power plants, and the unpredictability of fossil fuel prices. Studies on the influence of future electricity prices usually focus on traditional high-temperature DH systems and fossil-fuel combined heat and power plants [36–38]. Considering the wind power integration and changes in nuclear power, Romanchenko et al. [39] constructed six price scenarios toward 2030 and found significant increases in average price and price variations with the phase-out of nuclear power. The viability of HP is also sensitive to price changes, as demonstrated by the case studies on the existing DH systems in Finland [38]. However, the scope of the aforementioned studies is on large and centralized HP systems while the influence of uncertain prices on the ULTDHC and 5GDHC remains unclear.

Besides the changes from the national grid, the local district energy system will change by integrating available RE, such as rooftop photovoltaic (PV). In specific district energy system cases with certain RE profiles, the overall system cost and RE utilization rate were optimized by the temperature control in the network [34], active TES [40], and batteries [18]. These and other studies [41,42] on RE integration were conducted under the assumption that DHC systems and operating conditions would not change. The existing results on planning system transitions cannot be extrapolated directly considering the impact of uncertain local RE. Hence, the planning system transitions toward different options remain a question. As the overall system efficiency and the heat-to-power ratio will be improved, the ability to use the RE to achieve the synergy between electricity and heat remains unknown.

On the demand side, a future major change involves the change of the heating and cooling demands owing to the ongoing global climate change [14,43,44]. Despite the uncertainties in climate forecasts, the future climate will become warmer on average, which increases the cooling demand and decreases the heating demand [45]. This change will reduce the efficiency, thereby the attractiveness of conventional centralized systems while creating possibilities for local energy systems (e.g., 5GDHC). Nik et al. estimated uncertainties induced by different climate models on building energy performance [14]. Based on climate models and the degree–day method, Larsen et al. determined changes in heating and cooling demands in European countries. They concluded that the most significant changes were observed in the Nordic countries [12]. The above studies are mainly conducted from the perspective of buildings with the well-known impact of climate change on the theoretical heating and cooling demands. However, the performance and transitions under such changes are less considered at energy system levels. An optimal decision about transitions toward low-temperature systems shall be based on the foreseen changes in the demand to ensure a satisfying performance of DHC for a long time in the future.

Another significant change on the demand side is caused by building renovation measures, which were planned in many countries [46] and recognized as essential steps to reach the carbon neutrality target. Until now, deep renovations that reduce the energy demand of buildings by at least 60% are conducted at only 0.2% of the building stock per year across the EU [47]. Therefore, the EU Commission published a new renovation strategy in 2020 to double the annual energy renovation rates in the next 10 years [47]. With a reduction in heating demand and demand density, the optimal design of DHC systems is inevitably affected. Nguyen et al. [48] studied the total annualized cost (TAC) of three low-temperature district heating and ULTDH systems for a new residential area with four land exploitation plans. The 4GDH option was more cost-efficient than the ULTDH system when the demand density was lower. A similar relationship between demand and ULTDH system feasibility was also found in the case studies in Denmark [49,50]. As for the 5GDHC system, unlike other systems, the impact of building stock renovations has not been addressed. Although most studies focus on the districts with internally balanced heating and cooling demands [9,10], the advanced deep renovations will change the balance and alter the results valid in current situations. Therefore, under the influence of future renovations, the choice of optimal energy systems requires further investigation.

3 Transitions based on uncertainty and sensitivity analysis

The transitions of heating and cooling systems under future changes are analyzed in this chapter based on the research gaps discussed in the previous chapters. Uncertainties in space cooling (SC) and SH demands, equipment efficiencies, equipment costs, and energy prices are the four major uncertain parameters in the analysis. These parameters represent future challenges and changes from broader and local perspectives. A generalized methodological framework combining energy system optimization with stochastic simulations, uncertainty analysis, and sensitivity assessment has been developed for this purpose. The content of this chapter is based on the study presented in **Paper III**.

3.1 Uncertainty characterization

Stochastic combinations of different buildings within a hypothetical district have been identified to facilitate the investigation of uncertain demands and cases, as shown in **Figure 3.1**. The district is a square land with a side length of 500 m. Five plot ratios (PRs) (0.1–0.5) and a step increase of 0.1 are considered here. The total building floor area within the district is determined based on the assigned PRs, and the residential, commercial, and office buildings are stochastically combined to form the district-level demand cases. Thermal properties of materials and components in the building envelopes and ventilation rates are distributed uniformly within the ranges that are representative of the buildings in Sweden. The hourly schedules (indoor activity occupancy and temperature setpoint) vary uniformly by 20% from the empirical schedules. Heating and cooling sources, networks, TES units, and auxiliary equipment are correspondingly designed with different uncertain characteristics. A total of 130 demand cases have been identified. Demand densities and cooling demand shares in these cases are explained in the following paragraph. For every demand case, 1,000*N iterations (energy system optimizations) are performed to determine the sensitivities of uncertain parameters. N represents the number of uncertain input parameters, as shown in **Table 3.1**. Approximately 10,000 iterations were performed for every demand case. The energy system optimization problem is solved in every iteration. This arrangement is a good tradeoff between calculation efforts and accuracy for the uncertainty and sensitivity analysis [51]. The analysis was repeated for the four energy system options and the four design objectives were described earlier. Therefore, probability distributions of energy system performances and optimal designs under uncertain inputs are acquired, which are valuable to stakeholders and decision makers.

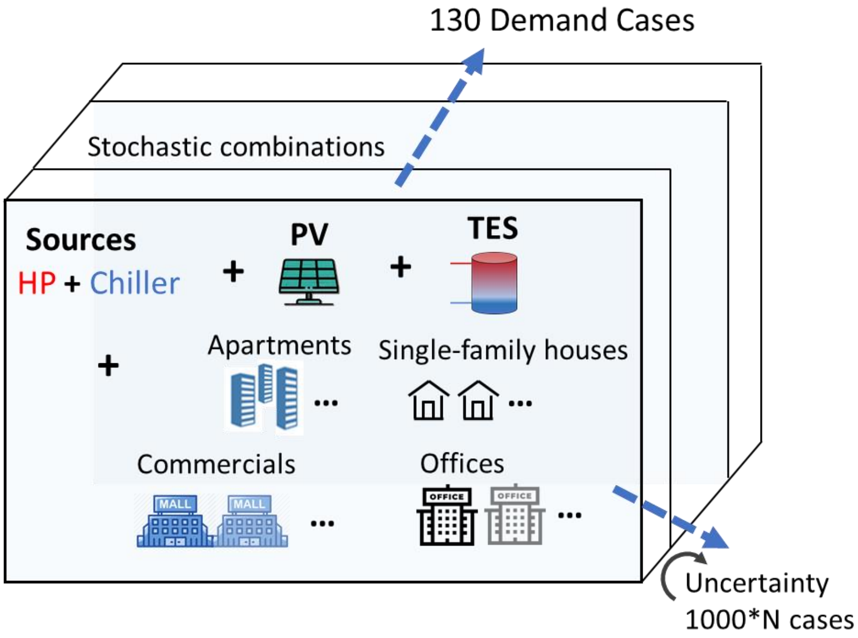


Figure 3.1. Illustration of the demand cases based on stochastic combinations of buildings. N represents the number of uncertain parameters.

Table 3.1. General distributions of uncertain parameters.

Category	Distribution
Demand	Discrete, 130 cases
Equipment efficiency	Uniform, 8 parameters
Equipment cost	Uniform, 13 parameters
Electricity price	Discrete, 45 cases

Besides the four building types, the hypothetic process cooling demands for commercial users, such as data centers and supermarket refrigerators, are considered within the district. The design cooling power ranges are assumed as 0–300 kW and randomly sampled in the simulations. More than 1,000 stochastic building combinations have been identified in this way. Combinations with similar demand densities or cooling demand shares are omitted from further investigations to reduce the calculation burden. Finally, 130 demand cases are selected, covering a wide range of demand densities, as shown in **Figure 3.2**.

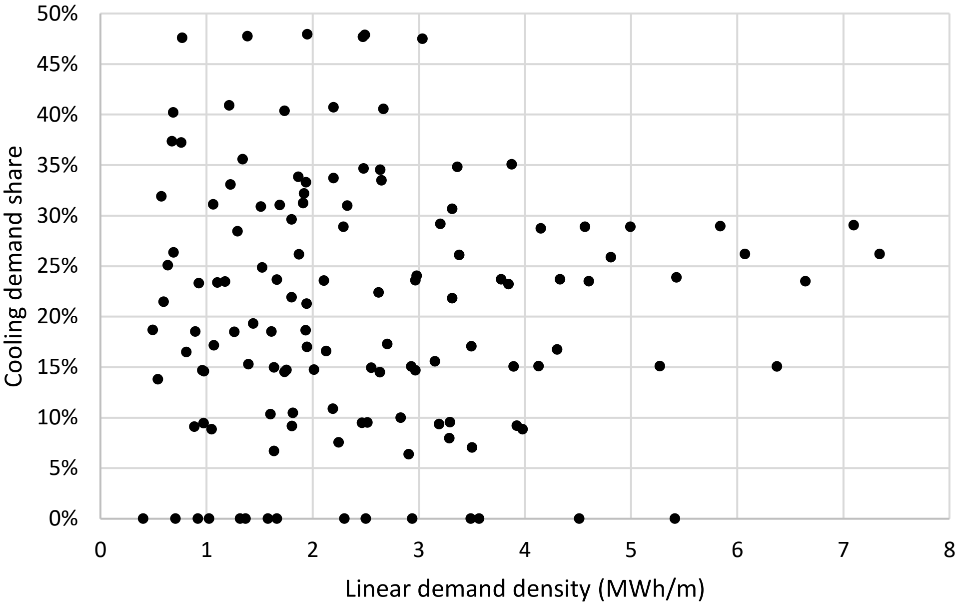


Figure 3.2. Linear demand density and cooling demand share of the selected demand cases.

The probabilistic density function that explains the range of values and the probability of occurrence is commonly adopted to depict the characteristics of future changes [27–29]. Herein, the uniform distribution is applied for the equipment efficiency and costs. A set of price profiles is created for energy prices, following a discrete uniform distribution. Subsequently, the input price in the model is randomly sampled from the predefined profiles.

All heating and cooling sources are assumed to be electricity driven to achieve power-and-heat synergy and simplify the choice of energy sources. The variety of equipment efficiencies is expressed by the differences in the COPs based on data from technical reports [52] and experimental studies [53,54]. The uncertain ranges are shown in **Table 3.2**. In addition, the investment ranges are derived from future forecast equipment prices [52,55,56], considering market development and technical progress, as shown in **Table 3.3**. However, the uncertain changes in interest rates and lifespan are not considered.

Table 3.2. Uncertain characteristics of COPs and investment costs for heating and cooling sources.

Technology	Description	COP		Investment (€/kW)	
		Min	Max	Min	Max
Central HP	In 4GDHC system, 65 °C forward temperature	3.1	5.2	300	600
Central HP	In ULTDHC and 5GDHC systems	6.5	10.4	600	1,000
Booster HP	In substations of ULTDHC and 5GDHC systems	4.9	6.8	600	1,600
Central chiller	Compression in 4GDHC and ULTDHC systems	3.1	5.4	300	600
Central Cooling	Back-up cooling source in 5GDHC system	3.5	15.3	100	600

Local chiller	In substations of the 5GDHC system	4.9	7.4	600	1,600
Air-source HP	In individual building-level system	2.5	4.7	600	1,200
Air-source chiller	In individual building-level system	3.1	5.1	800	1,400

Table 3.3. Uncertain characteristics of investment costs for the heat exchanger, TES units, and PV panels.

Technology	Description	Unit	Min	Max
Heat exchanger	In substations, including the auxiliary equipment	€/kW	50	150
TES	Large central water tank (>100 m^3)	€/m^3	600	1,400
	Demand-side building water tank (<1 m^3)	€/m^3	2,000	4,000
	Seasonal pit TES (>1,000 m^3)	€/m^3	10	50
Rooftop PV	Residential and small district use	€/kW	600	1,400

For electricity price uncertainties, the ELIN–EPOD modeling package generates variable price profiles, as explained in **Paper III** and [57]. The most significant factors for the electricity price levels are the growing power generation of RE, decommissioning of the nuclear power plant, possible increase in fossil energy prices, and variations in feed-in prices of local RE. Subsequently, uncertainties in the power technologies are stochastically combined as input parameters in the ELIN–EPOD model. Thereby, a set of price profiles is generated. Finally, 45 bought-in price profiles from the grid with unique characteristics are selected for further studies to limit the calculation effort, as shown in **Figure 3.3**.

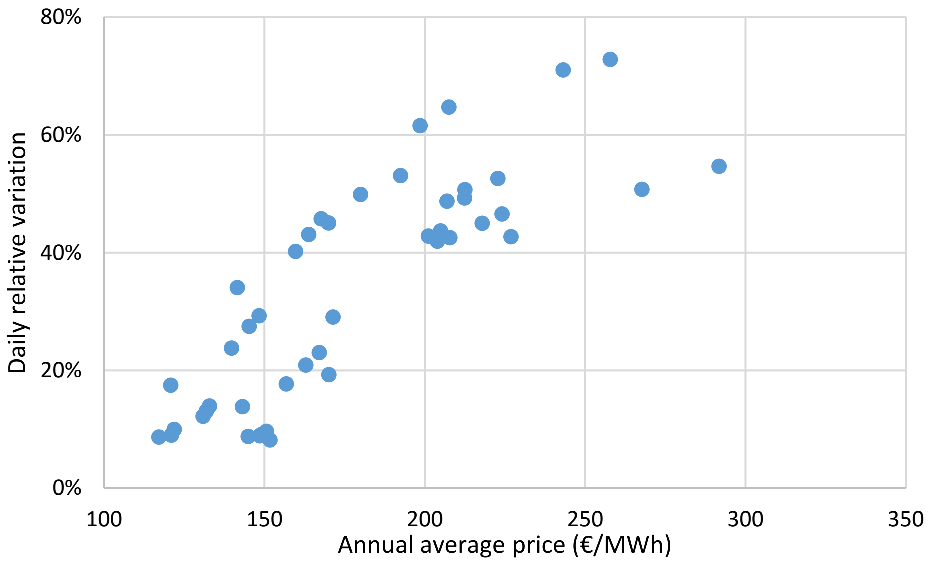


Figure 3.3. Annual average values and relative daily variations of the 45 price profiles.

3.2 Analysis methods

The methodological framework in this chapter comprises five significant steps, as shown in **Figure 3.4**. Step 1 includes the dynamic thermal models for DHC systems and the linear optimization problem to identify the optimal system design and operation. Step 2 defines four objectives (OBJs) for designing DHC systems, considering economic and environmental aspects regarding the TAC and imported electricity limit, respectively. As a significant contribution of this study, the uncertainty characteristics of the input parameters for the DHC systems are identified in Step 3. Stochastic combinations of uncertain parameters are inputs to the optimization model in Step 1. Based on these steps, Monte Carlo (MC) simulations are conducted in Step 4 to determine the general distributions of DHC performance and the sensitivities of uncertain input parameters. In Step 5, DHC systems are compared in several stochastic cases. The most significant factors for system transitions are identified, with the cost-saving probability (CSP) indicator.

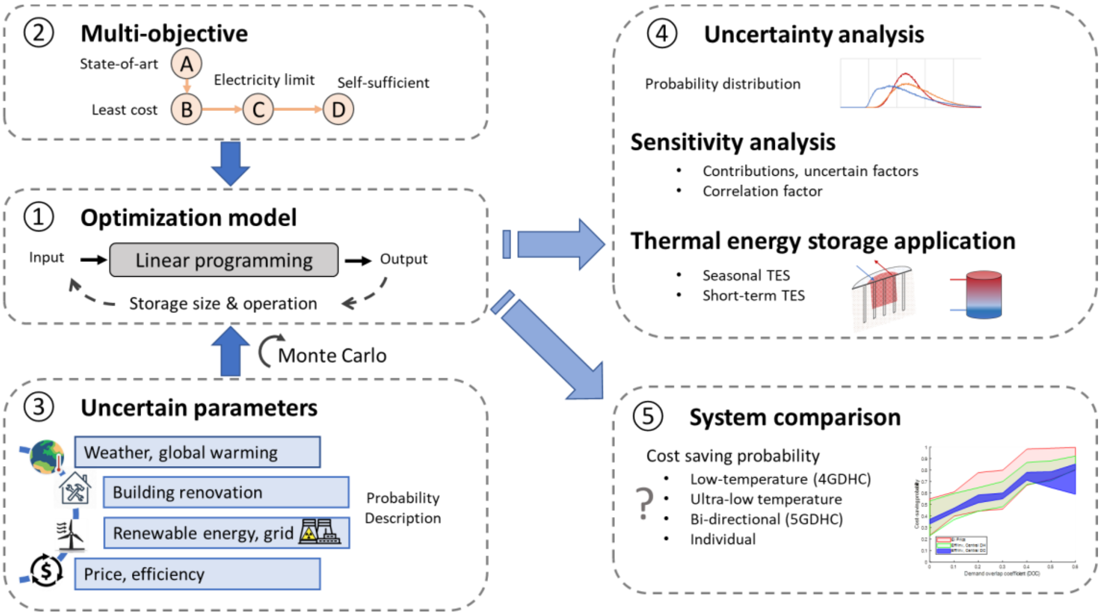


Figure 3.4. General methodological framework for uncertainty and sensitivity analysis for DHC systems.

The models for DHC systems are based on the transient and linearized thermal energy systems in **Papers I–III**. Each DHC network is represented by two thermal storage capacities for the supply and return lines. Hydraulic conditions such as pressure distributions over the network are not considered to linearize the system model and simplify the follow-up optimization process. A given heat loss rate of 0.1 $W/(m \cdot K)$ is used for transmission heat losses. For a stable system operation, the network temperatures are controlled to the design values by central heating and cooling sources in the investigated DHC systems.

The demand for SH and SC is calculated using a two-node capacity model with five resistances [58]. In this representation, each building is considered a thermal zone with a uniform air temperature. DHW draw-off profiles are generated using a stochastic modeling tool called DHWcalc [59]. Based on the profiles, the secondary DHW losses were calculated by assuming a representative length of circulation pipes and temperature difference [60]. Local equipment, such as heat exchangers and HPs, are operated with given temperature setpoints to fulfill the demand and losses.

The four design objectives of DHC systems are summarized in **Table 3.4**. The decision variables include the operation actions and design capacities. The former comprises the charging and discharging operations of TES units to use variable electricity prices, reduce peak power costs, and increase the use of RE sources. The latter refers to the capacities of DHC sources and TES units. The minimal time step is set as 1 h in accordance with the demand profile. The entire model is a mixed-integer linear problem, developed and performed in MATLAB, as shown in **Paper III**.

Table 3.4. Descriptions of the four objectives investigated in this study for designing the DHC system.

Objective	Description	Measure
A	Minimal overall system cost, no local RE	Heating and cooling systems
B	Use of local PV for the lowest annualized cost	Optimized PV capacity
C	Import electricity limit: 0.1 kWhe/1 kWh demand	Optimized PV + seasonal TES
D	Import electricity limit: 0.05 kWhe/1 kWh demand	Optimized PV + seasonal TES

Based on the uncertain input parameters and the system optimization model, more than one million iterations are created with MC simulations for uncertainty analysis. The indicator of contribution to total system cost is applied here to express the practical meaning of sensitivity as follows:

$$\sigma(X_n) = \frac{TAC(X_n) - TAC(X_0)}{TAC(X_0)} \tag{1}$$

where X_n and X_0 are uncertain parameters X at the investigated and reference values, respectively. **Eq. (1)** directly expresses the relative changes in TAC induced by the uncertain parameter X. The results from different uncertain parameters are comparable for sensitivity analysis.

In real projects, decision makers and system operators always question, “which system costs less.” CSP is applied to stochastically compare the economic performance of future DHC systems as follows:

$$CSP_{A,B} = \frac{\sum(TAC_A(z) \leq TAC_B(z))}{n_A \cdot n_B} \tag{2}$$

where A and B are the two compared sets of data, referring to the two different systems. z represents any case within the two sets. n_A and n_B are the total numbers of cases for sets A and B, respectively. With thousands of MC simulation runs, **Eq. (2)** expresses the probability of A having less TAC than B.

3.3 Key performance indicators

Energy system performance is usually influenced by numerous factors. To generalize these factors and to find the most influential ones, key performance indicators (KPIs) are presented. The sensitivities of KPIs for the ULTDHC and 5GDHC systems are also included, to improve the understanding of DHC system transitions.

Linear demand density, as shown in **Eq. (3)**, explains the heating and cooling demands on the unit length of the trench pipe. It distinguishes the feasibility of centralized and decentralized systems [50]:

$$q_l = \frac{Q_{heat} + Q_{cool}}{L} \tag{3}$$

DOC expresses the overlapping heating and cooling demands during a specific period *t* [10], as shown in **Eq. (4)**. This index identifies the economic attractiveness of the 5GDHC system [10,23]:

$$DOC = \frac{2 \cdot \sum_t \min\{P_{H,t}, P_{C,t}\}}{\sum_t (P_{H,t} + P_{C,t})} \tag{4}$$

An aggregated index named Eff/INV is defined to describe uncertainties in equipment efficiency and investment, as shown in **Eq. (5)**. This index expresses the heating and cooling source performance on unit investment cost and is applied to evaluate the influence of equipment uncertainties on energy system performance:

$$\frac{Eff}{INV} = \frac{COP}{Investment} \tag{5}$$

3.4 Results

For the four energy systems, the average levelized cost of energy (LCOE) and imported electricity of all possible cases under each objective are summarized in **Figure 3.5** as representatives of the overall performance. From objectives A to B, with the installation of PV panels for the lowest annualized cost target, the overall system LCOE decreases by approximately 2%. The imported electricity index describes the amount of electricity the grid needs to meet particular heating and cooling demands and is the inverse of the system efficiency. The individual system has the highest imported electricity index, whereas the 5GDHC system has the lowest, reflecting the difference in terms of system efficiency. With particular targets for electricity usage in objectives C and D, more capacities of PV panels and TES units are needed, regardless of their cost. Therefore, the overall system costs are increased. As the initial imported electricity index in the 5GDHC system is already low, the prospects of the extra equipment including PV and TES units achieving the same target are smaller than those in the 4GDHC and ULTDHC systems. Consequently, the difference in overall system cost between 4GDHC and 5GDHC increases from 4 €/MWh in objective A to 13 €/MWh in objective D.

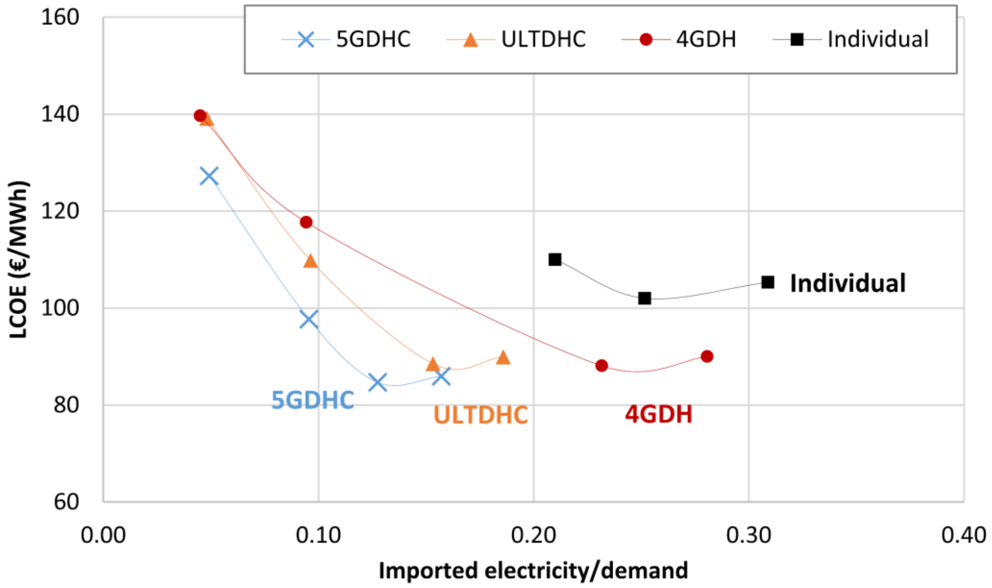


Figure 3.5. Levelized cost of energy (LCOE) and imported electricity for the investigated systems under four objectives. For each system, the dots from right to left represent objectives A–D, respectively, with a decrease in imported electricity.

System performance diversity based on stochastic simulations is shown in **Figure 3.6**, taking objectives A and D as examples. The 4GDHC and individual systems of objective A have wider ranges of LCOE and imported electricity than those of other DHC systems. These findings indicate that the two systems are more vulnerable to uncertain changes. Most cases with objective D are grouped within the imported electricity limit, whereas some cases fail to achieve the objective on electricity import. The main reason associated with the nonconforming cases in ULTDHC and 5GDHC systems is the use of decentralized equipment, such as the booster HP, circulation HP, and local chiller. These facilities consume approximately 12% and 38% of the total electricity demand in the ULTDHC and 5GDHC systems, respectively. Unlike the central TES units, the demand-side TES units have limited applications due to the relatively high investment and limited space use in the buildings [30]. Therefore, the electricity demand from decentralized equipment is difficult to be shifted using demand-side TES to incorporate the available PV power. For the ULTDHC and 5GDHC systems, more efficient demand-side energy storage technologies are required such as household batteries.

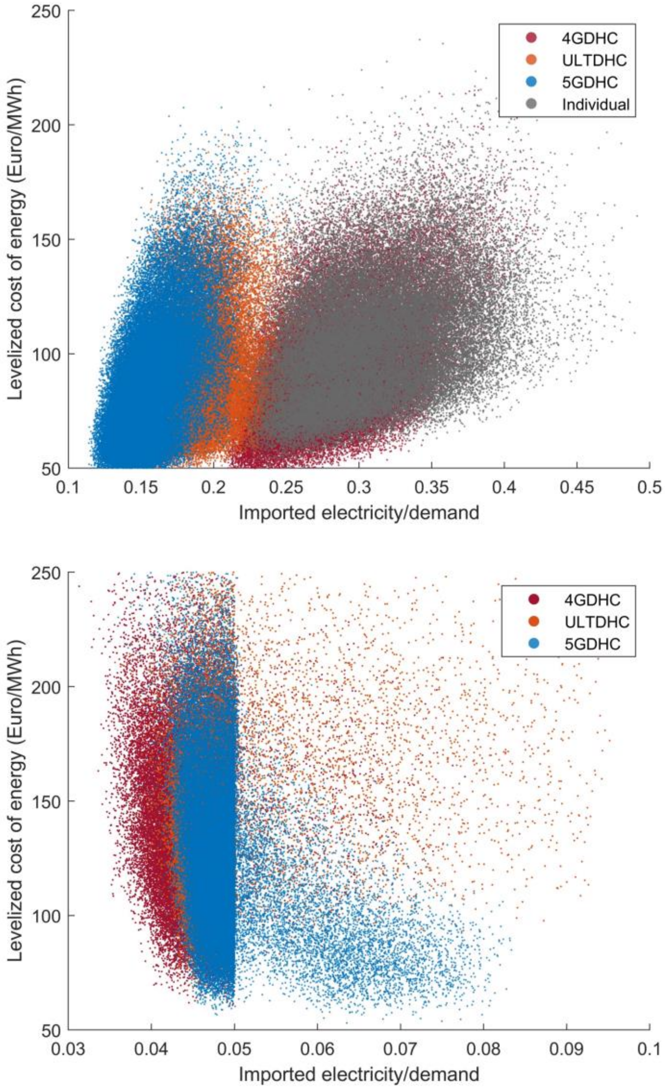


Figure 3.6. Scatter plots showing the economic performance (LCOE) and imported electricity of Monte Carlo simulation results for objective A (upper) and objective D (lower).

The sensitivities of demand profiles are revealed using Spearman's rank correlation coefficients between different KPIs and the system cost, as shown in **Figure 3.7**. Demand density (areal or linear) is the most sensitive parameter for the system cost, especially, for the three DHC systems. With more aggregated heating and cooling demand, the initial investment in the network and sources is better shared with end users. Accordingly, the Spearman coefficients between linear density and total costs lie between −0.6 and −0.8 in the three DHC systems. In contrast, the influence of demand density is relatively less significant for individual systems. The impact of DHW demand share is relatively small compared to other parameters. The DOC can better reflect the dynamic balancing potential of heating and cooling demands and is more appropriate for evaluating bidirectional 5GDHC.

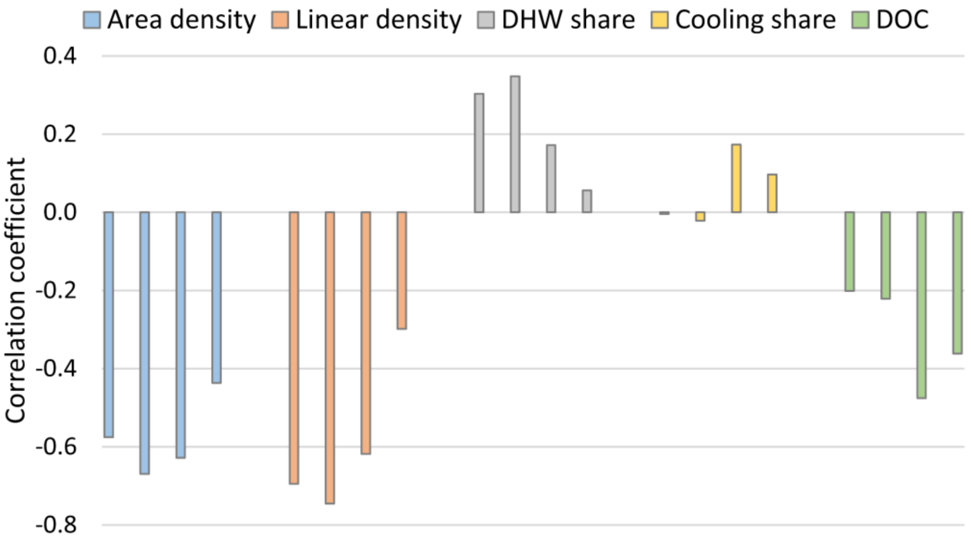


Figure 3.7. Spearman's rank correlation coefficients between specific demand KPIs and the total costs, with objective A. The four bars represent the four investigated energy systems: 4GDHC, ULDHC, 5GDHC, and individual.

The contributions to the system cost from electricity price and equipment investments are summarized in **Figure 3.8**. With objectives A and B, electricity price directly affects the system cost and is the most influential factor. With a high share of PV power in the entire system of objectives C and D, both the imported electricity from the grid and the impact of grid price are smaller. For the four energy system options, high efficiency means less electricity consumption, thereby less sensitivity to price changes. The individual system is mainly influenced by electricity price, whereas the 5GDHC is a robust technology for future price changes.

With strict requirements for RE utilization, the need for seasonal TES to balance the surplus PV power during summer is growing rapidly. Therefore, under objectives C and D, the contribution of TES investment to the system cost reaches 30%–60%, mainly driven by seasonal TES investment. Compared to other factors, the uncertainty associated with the investment in centralized heating and cooling equipment slightly changes the total system cost. This is caused by the application of centralized TES, whose main purpose includes reducing the peak power and associated cost. The differences between the three district systems are also small. Conversely, the contributions of the investment in local equipment are more obvious, as shown in **Figure 3.8** (d).

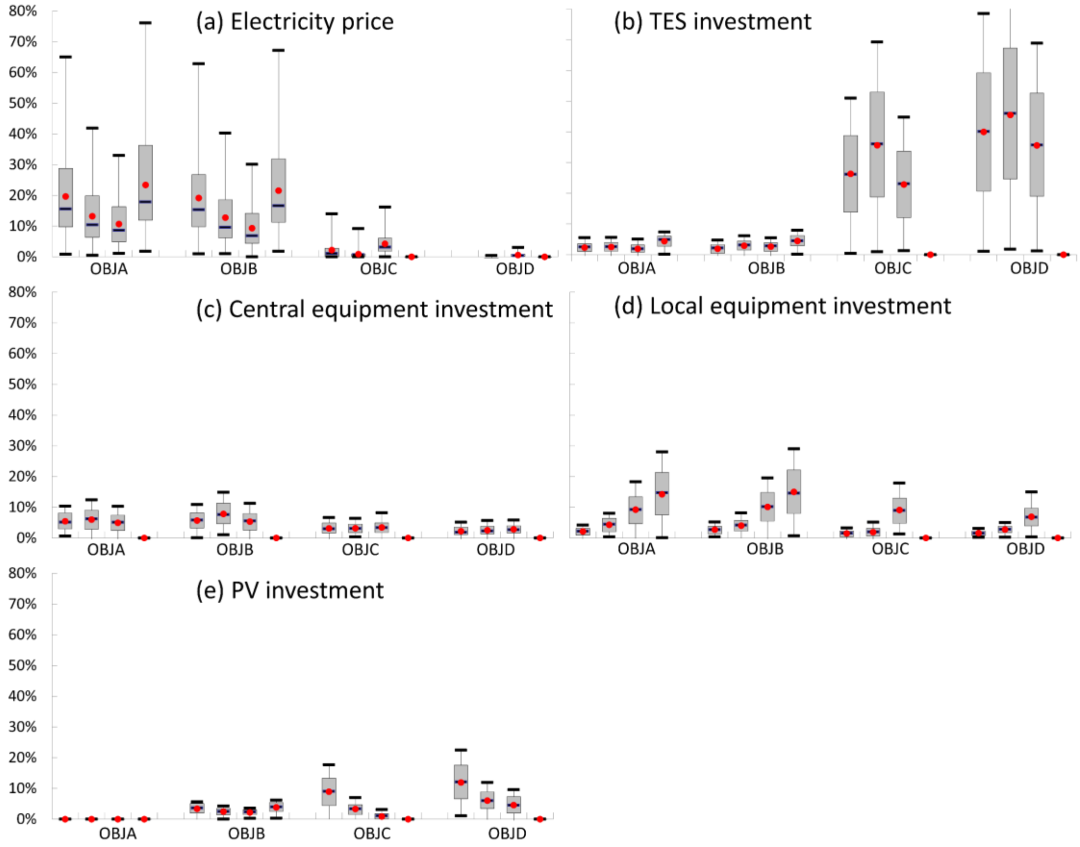


Figure 3.8. Box-plot presentations of contributions to the system total cost by electricity prices and equipment investments. The order of the systems is also present. For each objective (OBJ), the four bars represent the four investigated energy systems: 4GDHC, ULDHC, 5GDHC, and individual.

CSPs of ULTDHC, 5GDHC, and individual systems are compared to that of the 4GDHC system with objective A and presented in **Figure 3.9**. More detailed results on system comparison under objective D and discussions on the sensitivity of TES units are discussed in **Paper III**. For every pair-of-system comparison, the most significant factor indicated by sensitivity analysis is set on the horizontal axis. Contributions to CSPs from other factors are presented as ranges and marked in different colors. For simplicity, only the four most sensitive factors were considered in the system comparisons. Besides, there are small oscillations in the curves due to the uneven distributions of demand KPIs.

The CSP of the ULTDHC system compared to that of the 4GDHC system varies by approximately 50% and is affected by several factors. The probability distribution curves of the total costs of the two systems are close to each other. No single factor directly indicates the economic feasibility. However, the area demand density remains a key factor. The ULTDHC system is more likely to be cost-effective compared to 4GDHC in the area with high space-heating demand density because of the benefit of ultralow-temperature space heating supply. This corroborates previous studies on the feasibility of ULTDHC [50].

The DOC is the game-changing factor for the 5GDHC system. With a DOC index higher than 0.4, the 5GDHC system has an average 80% possibility of being cost-saving compared to the 4GDHC system. Therefore, the DOC can be an index to pre-identify the economic performance of 5GDHC [10]. According to the results presented in **Paper III**, the conclusion is resilient under different objectives. Moreover, the electricity price is an unneglectable factor for both ULTDHC and 5GDHC systems. When the average price is low, the benefits from saved operational expenditure cannot cover the relatively high equipment investment. Consequently, even with a DOC of 0.6, 20%–30% of occasions favor the 4GDHC system rather than the 5GDHC system. The electricity price for the ULTDHC system can alter the CSP by approximately 40%. Moreover, as the cooling demand increases, the efficiency and cost of cooling equipment become increasingly important.

Furthermore, the most critical factor for the economic competitiveness of the individual system is the linear demand density. With higher density, the cost of the heating and cooling network is more distributed to end users, which makes the centralized system economically attractive. On more than 50% of occasions, the individual system is more expensive than the 4GDHC system when the linear density is higher than 1 MWh/m.

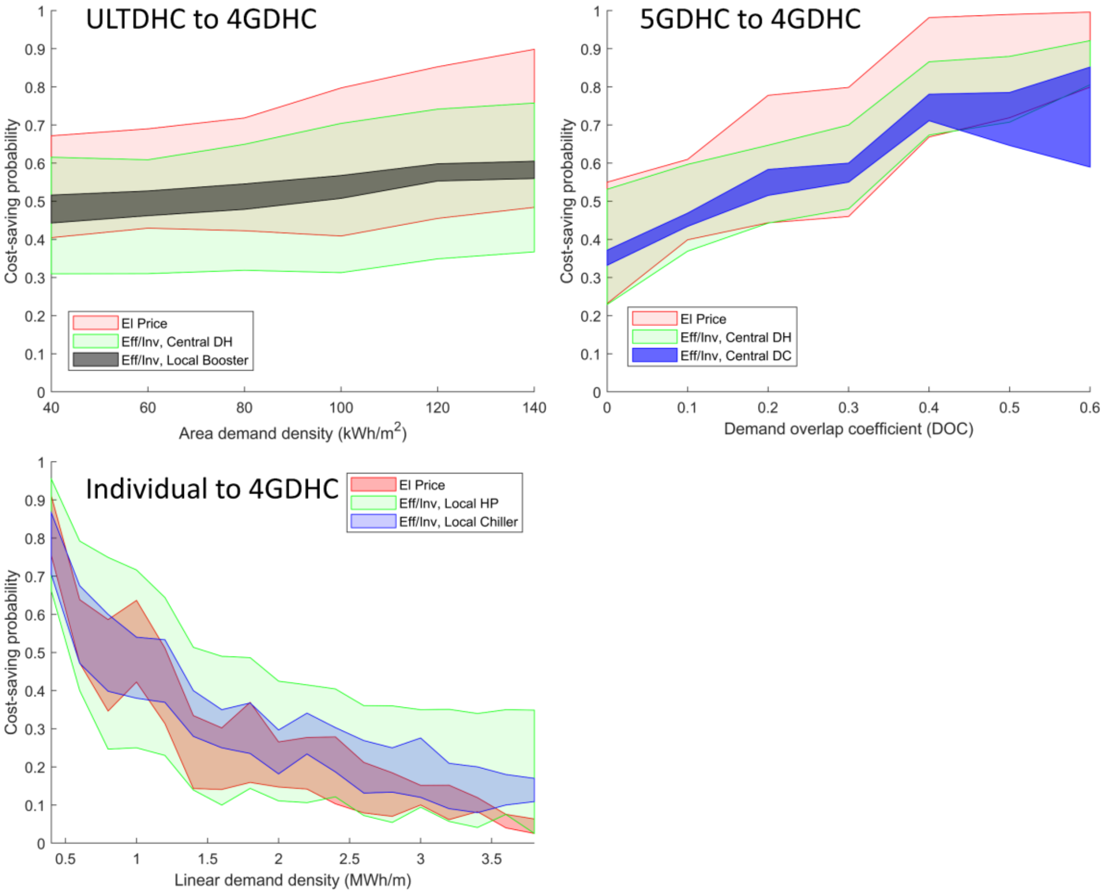


Figure 3.9. Cost-saving probabilities of ULTDHC, 5GDHC, and individual systems compared to 4GDHC, with objective A.

3.5 Transition roadmap

Based on the sensitivity analysis results and system comparisons as presented earlier, a summary of the key factors for the transition of 4GDHC to the ULTDHC, 5GDHC, and individual systems is shown in **Figure 3.10**. Here, the 4GDHC system is set as the reference system. For the ULTDHC and 5GDHC systems with large investment costs and high energy efficiency, the possible high electricity price in the future favors their applications because the savings from their operational cost can cover their investment cost. The specific promoting factor for the ULTDHC system is the high space-heating demand density because it highlights the benefit of lowering the supply water temperature. As presented with the DOC index, the overlapping heating and cooling demands largely determine the transition to the bidirectional 5GDHC system. Because TES has limited roles in achieving power-and-heat synergy in the ULTDHC and 5GDHC systems, the uncertainties in the TES cost are possible future hindering factors for these new DHC systems.

The individual system mainly applies to the area with low demand density. Moreover, improvements in equipment efficiency and costs can increase the feasibility of the individual solution but only to a limited extent. Due to the difficulty of applying large-scale centralized TES units, the integration of RE is much harder to achieve in the individual system compared to that of the other systems.

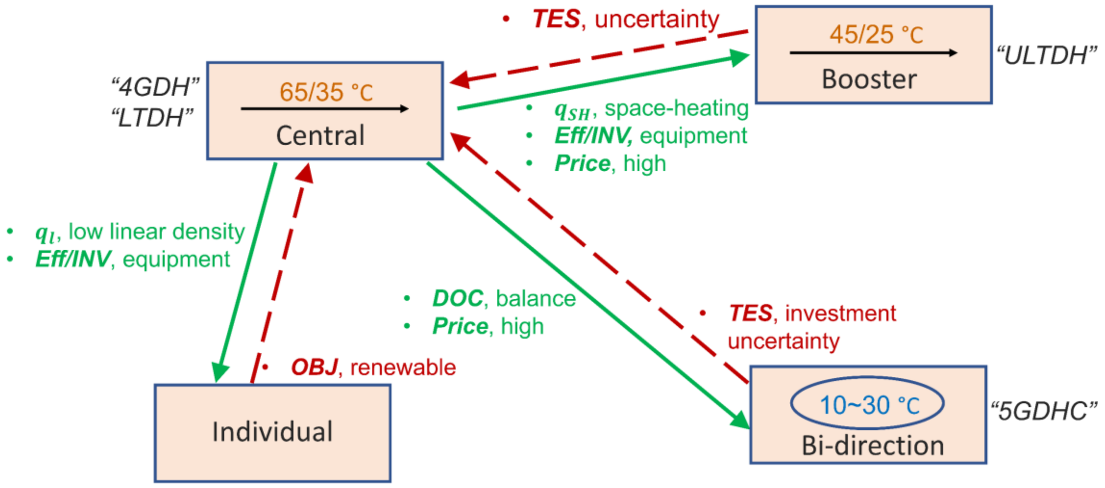


Figure 3.10. Roadmaps for energy system transitions identified through the promoting (green) and hindering factors (red).

4 Potential applications of 5GDHC

Based on the main factors for planning the future DHC systems in **Chapter 3**, the potential of the 5GDHC system on the existing European building stock is analysed using a geographical information system or GIS-based method. EU 27 countries, the UK, and European Free Trade Association countries are included in the investigation. This chapter also considers the applications under future scenarios for the demand side. Based on the results, the roles of the 5GDHC in the future are quantified and the potential sites are geographically mapped. This chapter is based on the appended **Paper IV**.

4.1 Data source and analysis methods

The hectare-level demand densities and floor area are derived from the open-source toolbox Hotmaps [61]. As a starting point, the toolbox provides the gross floor area (GFA) at a resolution of 100 × 100 m covering the entire investigated European countries [62] in 2016. After excluding the rural area with no buildings, 28 million hectare-sized units are included in the database. Data are based on aggregated floor area at the country level and are organized considering population density [63], land-use data [64], the European Settlement Map layer [65], and data from the OpenStreetMap database. Data related to buildings are classified into the residential and service sectors. Furthermore, the land-use data for 1975, 1990, 2000, and 2014 from the Global Human Settlement project [66] are used for the share of buildings per construction period. This chapter introduces general methodologies, and detailed processes are discussed in the toolbox report [62]. A summary of the main databases is shown in **Table 4.1**.

Based on the GFA data, the heating and cooling demand densities are analyzed considering the building stock characteristics, the digital elevation model, the local climate data, and the distribution of population density. However, the assessment of SC demand density is difficult because the cooled floor area is hardly known [67,68]. The heated and cooled floor areas are collected from multiple sources [69–71] and cross-checked to resolve this issue. The resulting cooled floor area ratios for the residential and service sectors are 6.7% and 27.4%, respectively, which are close to the estimations in [67]. With the impact of heatwaves in Europe, the future possible growth of the cooled area is explained in **Chapter 4.2**.

Table 4.1. A summary of the main databases used to analyze the potentials of 5GDHC.

Name	Description	Database
Demand density	SH, SC, and DHW at the hectare level	Hotmaps [61]
Gross floor area	Residential and service	
Climate	Various pathways toward 2050, 12.5 km resolution	CORDEX [72]
Renovation	Annual renovation rate at the country level	Renovation wave [73]

Furthermore, this study considers the refrigeration demand required by specific processes in service buildings, such as supermarkets and data centers. This demand is noted as process cooling and is considered a key factor in the 5GDHC system. A general proximation methodology based on the GFA density of service buildings, specific building types, empirical cooling demand for each building type, and aggregated country-level demand [74,75] is used due to the lack of locally available data. In addition, process cooling is not considered in residential buildings.

Hourly demand profiles are needed to obtain the overlapping temporal demand from an annually aggregated value. Generally, the hourly profiles are based on hourly temperature data and empirical demand profiles that reflect the consumer behavior acquired from the Hotmaps database [61]. The profiles are provided on the second level of Nomenclature of Territorial Units for Statistics in Europe (NUTS-2). Notably, the investigated SH and SC demand profiles are hypothetic, whereas several factors impact the practical profiles, such as the thermal inertia of the buildings and network. For DHW demand, empirical profiles are applied based on field investigations in Germany’s building stock.

The overlapping demand for every hectare unit and the index DOC is calculated according to the methods discussed in **Chapter 3.3**. Previous studies [10,76] and the uncertain analysis results in this work have proven the strong relationship between DOC and 5GDHC feasibility. Therefore, three selection rules are chosen based on DOC and demand density values, as shown in **Table 4.2**. The DOC criteria of 0.2 are considered the lower limit for 5GDHC application as the possibility of 5GDHC, which is more cost-saving than that of 4GDHC, is 50%, as shown in **Figure 3.9**. The DOC value of 0.3 is assumed as a further attractive point because 5GDHC is more energy-efficient [10] here. Higher DOC values are omitted for the identification rules because the area with DOC larger than 0.4 is rare in the European building stock, as explained in **Chapter 4.3**. The DHC system is more attractive than individual solutions in places with large floor areas and high demand densities. Two levels of total demand density are directly used as criteria. Considering an average area demand index of 120 kWh/m^2 in Europe, the two demand densities can be considered building area densities in the inner city and suburban areas, corresponding to the PRs of 0.42 and 0.25, respectively.

Table 4.2. Rules of identifying the potential areas for 5GDHC system application.

	DOC	Demand density
Rule 1	>0.2	>500 MWh/hm^2
Rule 2	>0.3	>500 MWh/hm^2
Rule 3	>0.3	>300 MWh/hm^2

4.2 Future scenarios

A summary of key characteristics of the future changes considered for the European building stock is shown in **Table 4.3**. The low and intermediate representative concentration pathways (RCP), namely, RCP 2.6 and RCP 4.5, respectively, represent different climate futures. The moderate scenario is based on RCP 2.6 and uses the yearly profile close to the 10-year average level of the 2050s. For RCP4.5, the year with the highest annual average air temperature of the 2050s decade is used, as a representative of the extreme scenario. These climate data are based on the regional climate model RCA4 and the global climate model ECHAM6 [77].

Table 4.3. Summary of key characteristics of future changes considered for the building stock.

Category	Name	Description
Climate	2050	RCP 2.6. The year close to the 10-years average level
	2050e	RCP 4.5. The extreme year with highest average temperature
Renovation	Slow	Current speed, deep renovation 0.2%
	Fast	Ambitious speed, deep renovation 1%
Cooling area	Current	12% of the gross floor area
	Increase	20% of the gross floor area

The degree–day method is applied to measure future heating and cooling demands. The changes in SH demand are assumed to be proportional to the changes in heating degree days (HDDs) [78], as shown in **Eq. (6)**. A similar assumption is also considered for the changes in SC demand and cooling degree days (CDDs). The HDDs are calculated for the heating period (October 1 to March 31), and the CDDs are calculated for the cooling period (April 1 to September 30). For the DHW and process cooling demands, no changes are considered for the future due to their relatively stable demand profiles:

$$\frac{Q_{SH,2050}}{Q_{SH,2016}} = \frac{HDD_{2050}}{HDD_{2016}} \tag{6}$$

Concerning the changes in the building stock, two scenarios toward the year 2050 with different renovation plans are of interest. The main difference lies in the plans for deep and medium renovation measures, as shown in **Table 4.4**. The energy savings associated with the two measures are over 60% and between 30%–60% [79], respectively. The slow scenario represents the renovation speed before 2020, which is considered far behind if the EU wants to achieve its 2030 climate target. The SH demand densities after renovations in the year 2050 are calculated based on the share of building ages at the hectare-level unit, the specific renovation measures, and the energy-saving benefits.

Table 4.4. Two renovation scenarios and general plans for deep and medium renovation.

Name	Plans
Slow	Deep: current speed (~0.2%) on buildings before 1975
	Medium: current speed (~1%) on buildings during 1975–1990
Fast	Deep: annual 1% on buildings before 1990
	Medium: 2× current speed on buildings during 1975–1990

The aggregated SH demand by building age is shown in **Figure 4.1**, with the moderate RCP 2.6 climate scenario in 2050. Approximately 50% demand reduction is observed in the fast renovation plan, which is close to the proposal to achieve the carbon neutrality target [2,47].

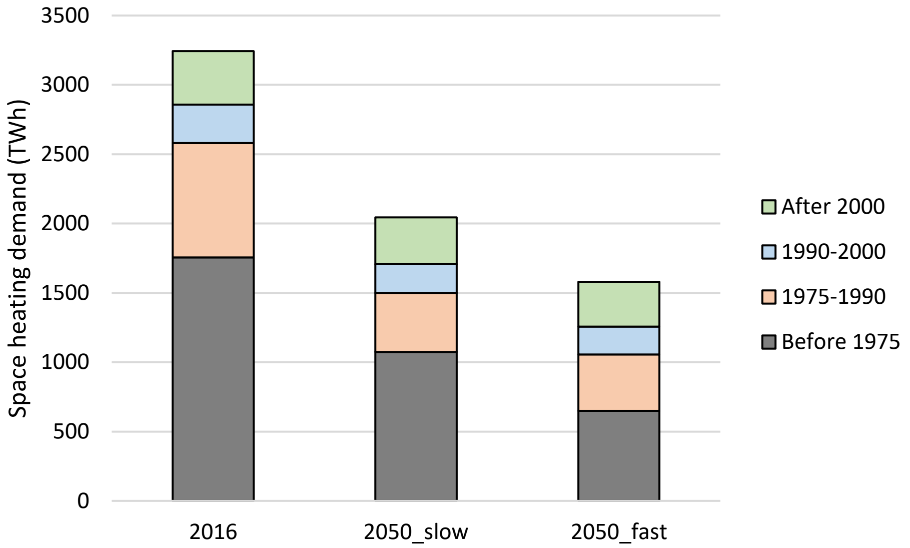


Figure 4.1. Aggregated space heating demand by building ages for the reference year (2016) and the future (2050).

Currently, approximately 12% of the EU building stock has SC. The number of air-conditioning units is increasing rapidly in Europe owing to heatwaves and increasing requirements for indoor comfort during summer. The scenario that has doubled the cooled area compared to the reference condition is considered to reflect such changes in the future. For the service sector, as the cooled area ratio is already larger than 50% in some countries, SC growth is less significant than that in the residential sector. In general, 20% of the EU building stock has SC demand in the cooled area increase scenario. The planned cooled ratio at the country level is downscaled to all hectare units inside.

4.3 Results

The overlapping heating and cooling demands are calculated for all hectare-sized units based on the aforementioned methodologies. The units are classified into different groups as per DOC ranges to better present the results, and the share of floor area for each group is shown in **Figure 4.2**. Most hectare units have DOC less than 0.1, which means they are almost inappropriate for applying the 5GDHC system. Less than 0.1% of the building stock has DOC larger than 0.3, which is regarded as the threshold for the energy-efficient 5GDHC system in previous studies [10,23].

A comparison between the two scenarios reveals that process cooling can increase the overlapping demand and the DOC index. This finding is explained using the structures of load profiles. For most European countries, the SH demand exists in winter, whereas the SC demand exists in summer. The overlapping part mostly comes from the relatively small DHW demand during summer, when heating and cooling is needed simultaneously. Given the process cooling persists throughout the year, high possibilities for simultaneous heating and cooling supply exist. However, the overlapping demand remains relatively small in terms of the existing European building stock. Approximately 14,000 hectare units have DOC larger than 0.4 corresponding to 0.03% of the total building area on account of process cooling. Some of these units are located in rural areas with a small amount of heating and cooling demand. The overlapping and aggregated demands in the reference scenarios without and with process cooling are 118 and 304 TWh, respectively.

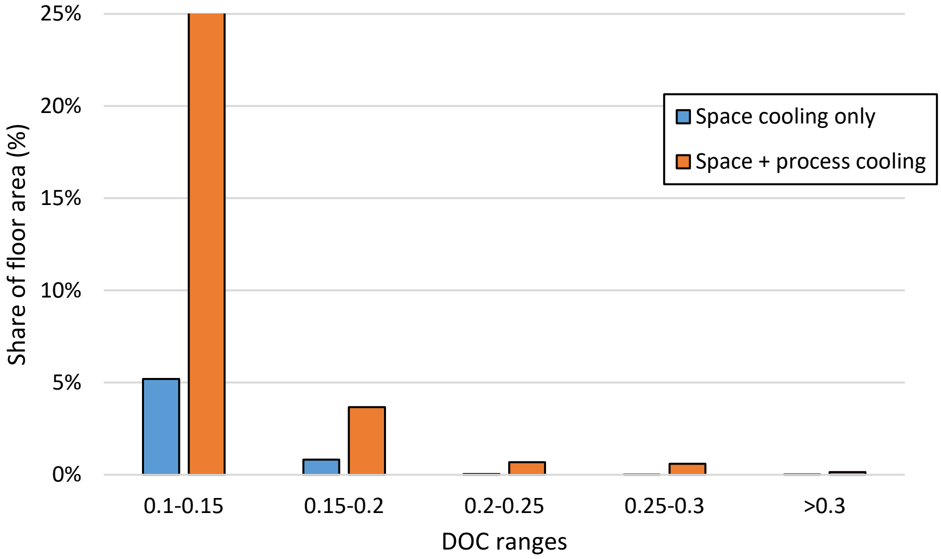
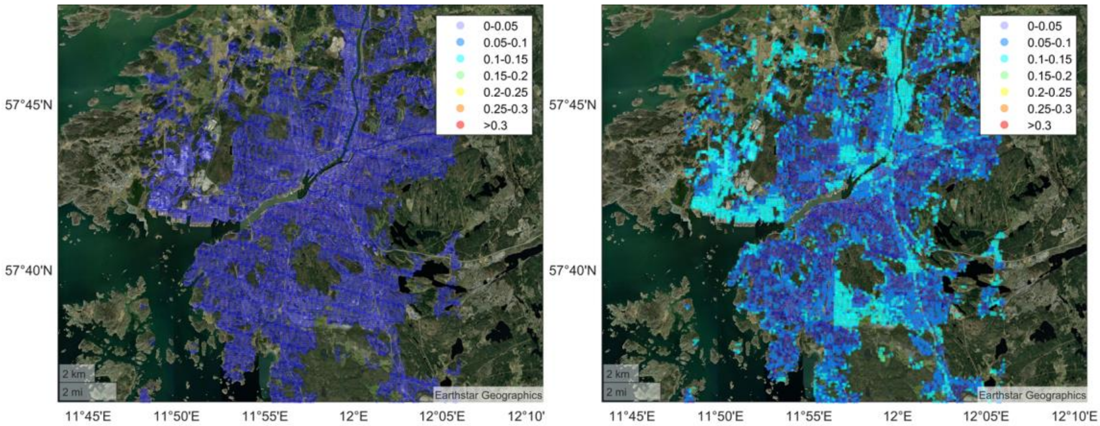


Figure 4.2. DOC ranges and the corresponding building area share in the whole studied European region.

The geographical distribution of DOC in the reference scenarios is shown in **Figure 4.3**, using the Gothenburg area as an example. The city is located on the west coast of Sweden. Considering process cooling, a few areas have DOC larger than 0.2, all located in the central parts of the city or the nearby suburban centers. Notably, almost no hectare-sized unit has DOC larger than 0.3 because the heating demand remains dominant in the Nordic countries, which explains why the units with larger DOC values exist in the city center. The suburban areas with large DOC have only a small practical demand density. Therefore, the two indices, DOC and demand density, shall be combined to evaluate the 5GDHC potential.



(a) 2010_ref
Space cooling only

(b) 2010_ref
Process cooling

Figure 4.3. DOC in the Gothenburg area.

With the changes summarized in **Chapter 2**, the overlapping demands of the European building stock in future scenarios are shown in **Figure 4.4** and classified according to DOC ranges and the shares of floor area. Despite the drastic changes in the SH and SC demand, the majority of the building stock still has DOC lower than 0.2, which is considered infeasible for 5GDHC. The changes in SH and SC mainly exist in two separate periods, thereby slightly affecting the overlapping demand. From another perspective, the share of overlapping demand will increase in the future with the decrease in the total SH demand. The share of the area that has DOC larger than 0.2, has a maximum value of 12.2% in the scenario with a fast renovation plan and current cooling area. However, most changes occurred in the DOC range of 0.2–0.25. The area with DOC larger than 0.3, which is the threshold for 5GDHC being energy-efficient, has less than 1% of the entire building stock. If the DOC is larger than 0.4, the share of floor area becomes 0.1%–0.2%.

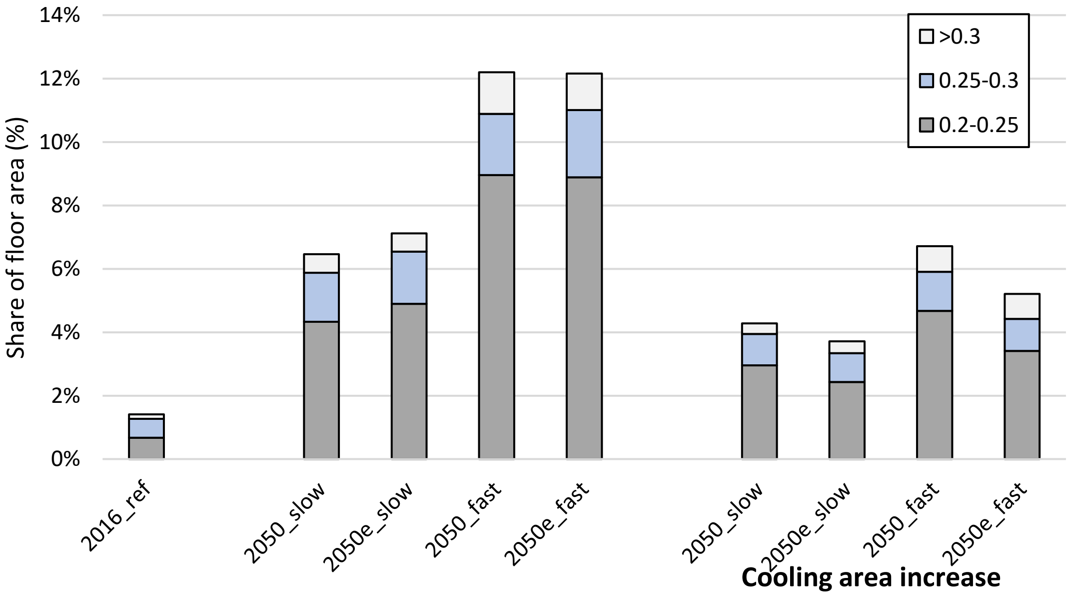


Figure 4.4. DOC ranges and the corresponding shares of building area in the whole studied European region.

Based on the three rules given in **Table 4.2**, the hectare-sized units meeting the requirements are selected and shown in **Figure 4.5**. From the entrance threshold of rule 1 to the stricter requirements of rule 2, the number of available units and corresponding floor area are significantly reduced, as shown in **Table 4.5**. For the fast renovation scenario with the largest overlapping demand, approximately 2,500-hectare units are identified as potential areas for 5GDHC application. With less stringent requirements for demand density in rule 3, the potential number of units increases slightly compared to that in rule 2, meaning that more suburban areas are included. However, compared to the entire building stock with a total floor area of 28,990 million m^2, the potential area of 5GDHC takes only a small share. In addition, although tens of thousands of hectare-sized units have DOC larger than 0.4, almost none meet the demand density criteria. They are mainly located in suburban areas with small demands and are not suitable for the 5GDHC system.

Table 4.5. Aggregated floor area and total demand of hectare-sized units meeting selection rules 1–3 under slow and fast renovation scenarios.

Rule	Scenarios	Number	Floor area (million m^2)	Total demand (TWh)
Rule 1	2016_ref	2,702	24.5	1.7
	2050_slow	29,678	304.6	22.5
	2050_fast	84,485	890.7	68.2
Rule 2	2016_ref	51	0.6	0.03
	2050_slow	428	3.9	0.3
	2050_fast	2,598	24.9	1.7
Rule 3	2016_ref	408	3.1	0.2
	2050_slow	2,048	12.6	0.9
	2050_fast	10,204	66.4	4.6

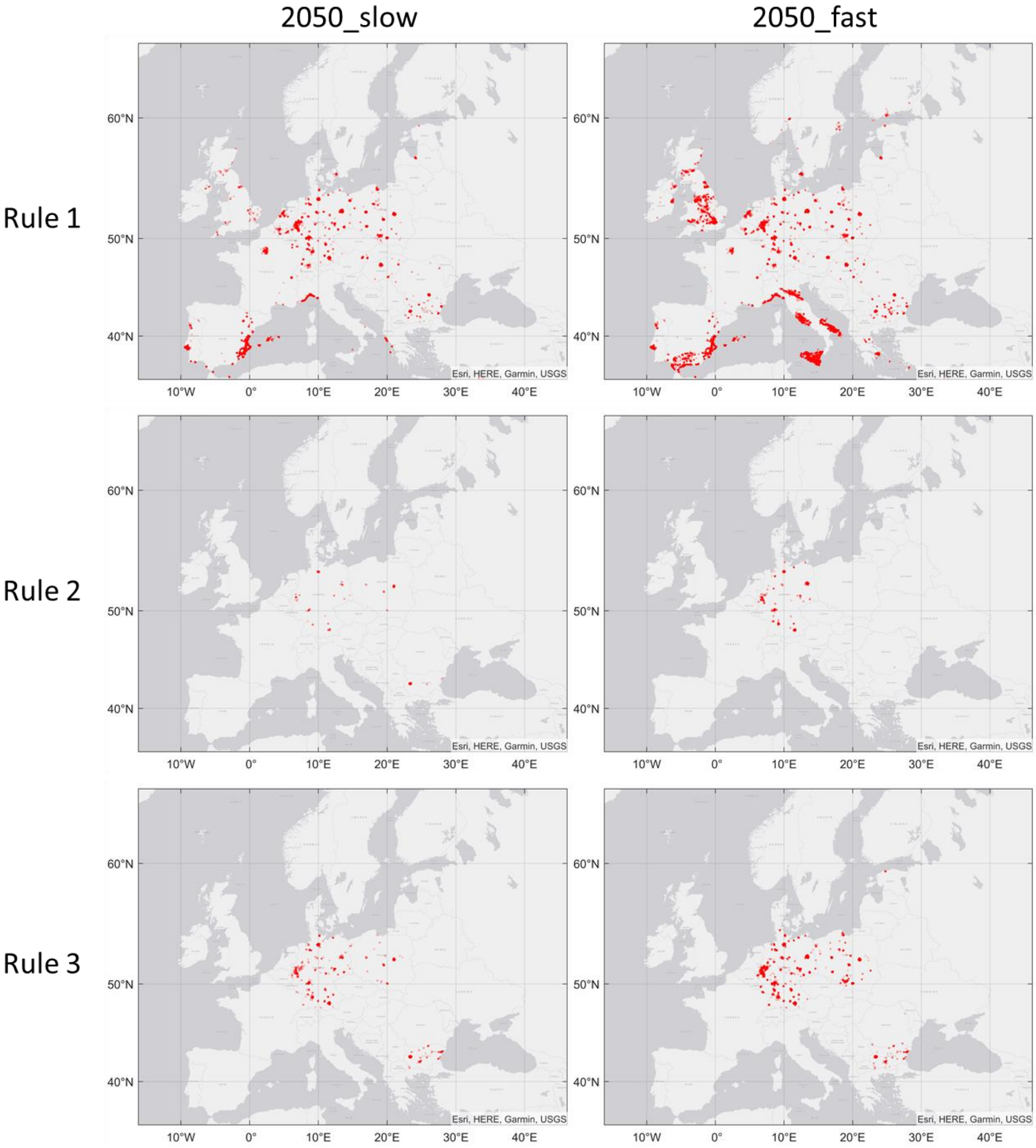


Figure 4.5. Geographical distributions of hectare-sized units meeting selection rules 1–3 under slow and fast renovation scenarios.

5 The role of TES with transitions

TES units have been widely used in DHC systems. Their roles in achieving economic and environmental objectives are modeled and analyzed in **Papers I–III**. However, owing to the different applied scenarios and systems, the acquired benefits of TES have shown large variations. Despite the knowledge about the utilization of TES in traditional 3GDH, the optimal planning of TES with the transitions towards future DHC solutions is still missing. This chapter aims to solve this question by introducing a simplified yet robust evaluation method for the TES in complex and changing DHC systems. The method combines top-down benefit analysis and bottom-up characteristic specification. The effectiveness of the proposed method is explained using three typical cases.

5.1 Evaluation method

The evaluation method focuses on an economic perspective. The main goal is to balance the top-down benefit and bottom-up TES investment. In other words, the foreseen benefit shall be larger than the associated investment to make the TES application feasible. Therefore, the objective is transformed into finding robust ways of evaluating the costs and benefits of TES, which should be simple and easy to use compared to complex case-specific modeling and optimization work.

Generally, the benefit of TES is classified into two categories, the energy-shifting benefit and power-shifting benefit. The former comes from the price difference of energy, such as the integration of cheap RE the replacement of high-cost fossil fuels, and the shifting of electricity demand to reduce cost. However, the latter benefit comes from the shifting of power, such as the peak shaving effect and the buffer storage unit, to avoid a huge initial investment.

The energy-shifting benefit can be expressed through the product of shiftable energy $Q_{price,T}$ and price difference, as shown in **Eq. (7)**. The shiftable energy can be further expressed as a function of hourly price Pr_t, demand profile $P_{t,demand}$, and storage cycle T, as shown in **Eq. (8)**. A straightforward explanation is that for a given time cycle T, the accumulated demand over high- and low-price periods can be calculated separately. Then, the shiftable energy is the minimum value of the two accumulated demands

$$REV_{price,T} = Q_{price,T} \cdot \left(Pr_{high,T} - Pr_{low,T}\right) \tag{7}$$

$$Q_{price,T} = f\left(Pr_t, P_{t,demand}, T\right) \tag{8}$$

The main equation for evaluating the benefit of RE integration is the same as **Eq. (7)**, whereas the function **Eq. (8)** is slightly different. If the RE is considered, the shiftable energy $Q_{sur,T}$ can be further expressed as the dynamic balance between RE supply and demand, as written in **Eqs. (9)–(11)**. For the second category (i.e., the power-shifting benefit), the revenue is calculated similarly to **Eq. (7)**. The price difference refers to the cost of different power (e.g., the annualized investment cost of equipment). The benefits of TES can be evaluated using these methods by knowing only the supply and demand profiles and the related prices.

$$Q_{sur,T,pos} = \sum_{t \in T} \left(P_{t,RE} - P_{t,demand}\right), if\ P_{t,RE} \geq P_{t,demand} \tag{9}$$

$$Q_{sur,T,neg} = \sum_{t \in T} \left|P_{t,RE} - P_{t,demand}\right|, if\ P_{t,RE} < P_{t,demand} \tag{10}$$

$$Q_{sur,T} = \min\left(Q_{sur,T,pos}, Q_{sur,T,neg}\right) \tag{11}$$

Concerning the bottom-up method for calculating the investment costs of TES, an active storage capacity is first discussed. Generally, the active energy storage capacity is usually smaller than the total TES capacity because of practical issues, such as energy losses and energy conversion efficiency, as illustrated in **Eq. (12)** and **Figure 5.1**. The power-to-heat conversion efficiency η_{p2h} of the entire DHC system is considered to express the synergy between the electricity and thermal sectors. This index describes the amount of electricity needed to produce a unit amount of heat. If TES is used for the thermal system alone, the conversion efficiency is 1. Otherwise, the index is smaller than 1, and the resulting converted electrical storage capacity is smaller than the TES capacity.

The thermal efficiency $\eta_{thermal}$ describes the available storage capacity considering heat losses, influenced by the storage characteristics and practical thermal insulation levels. This value could be approximately 90% for the large central storage unit owing to better insulations. In small-sized distributed household water tanks, the insulation investment per unit volume becomes much higher, and the efficiency decreases to approximately 80%.

Because of the unavoidable mixing of heat carriers inside the storage unit and the requirements for the supply and return water temperatures, only part of the total storage capacity can be actively used, as described by the exergy efficiency η_{exergy}. The range of this value is typically 70%–90% [80], although it can be improved by enhancing the temperature stratifications inside the storage unit using novel structural designs [81]:

$$C_{TES} \cdot \eta_{thermal} \cdot \eta_{exergy} \cdot \eta_{p2h} = C_{ES} \tag{12}$$

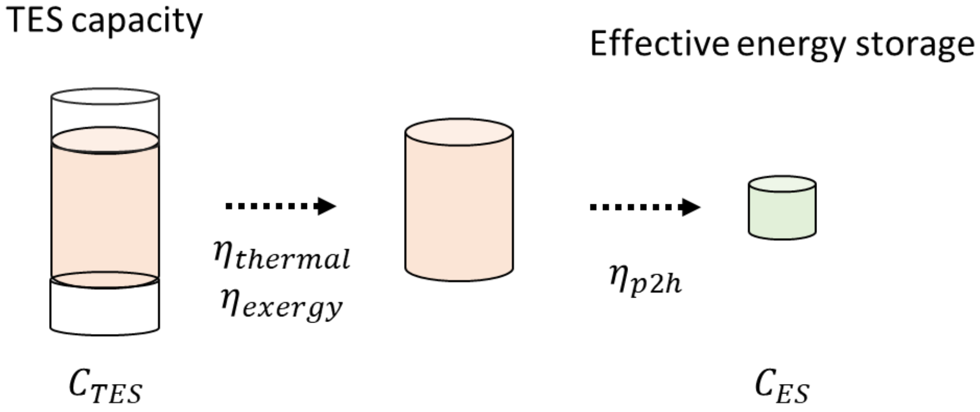


Figure 5.1. Illustrative diagram of the relationship between TES capacity and effective working storage capacity.

The investment of TES per energy storage capacity is commonly used in technical reports or scientific publications to evaluate the cost of TES. Herein, the unit cycle TES cost INV_{cy} is proposed as a standardized way of expressing the discounted investment on a single charge–discharge cycle. As shown in **Eq. (13)**, the initial investment per volume INV_V is modified by the annuity factor ANF, full-load cycles per year FLC, and a product of the systems' efficiencies explained earlier. The proposed cost refers to the unit's effective energy storage capacity. As explained above, the revenue of TES is connected to effective storage capacity and price differences. Accordingly, the bottom-up investment can be easily compared with the top-down benefit:

$$INV_{cy} = \frac{INV_V \cdot ANF}{\rho_{TES} \cdot FLC} \cdot \frac{1}{\eta_{therm} \cdot \eta_{exg} \cdot \eta_{p2h}} \tag{13}$$

5.2 Typical examples

The proposed method is applied to three typical examples that include centralized and decentralized scenarios. Sensitive parameters of the TES applications vary to show the method's effectiveness in evaluating the TES in the changing environment.

Example 1 refers to a large water tank, as TES typically used in centralized DHC systems. The TES parameters of such sizes and the benefits of the three typical application scenarios are shown in **Table 5.1**. The standardized unit cycle investment of TES is calculated using the abovementioned methodology. To reflect future uncertainties on the technical and economic performance of the TES, a range of relative changes in the investment and storage efficiency is considered and the resulting standardized cost is calculated, as shown in **Figure 5.2**. For benefit evaluation, scenario 1 refers to the thermal-only system where the TES shifts the relatively cheap heat to replace regular heating sources with an average price of approximately 0.1 €/kWh. The other two scenarios represent the synergy between electricity and thermal energy, considering different power-to-heat efficiencies.

The results show that the central water tank is economically feasible with application scenarios 1 and 2, which explains its widely distributed usage in DH systems. However, with the decrease in η_{p2h}, the same TES capacity can only produce lower effective capacity and lower shiftable electricity. Hence, in a high-efficiency system, such as 5GDHC, with high COP values, the active shifting of electricity using TES is more difficult to achieve. The improvement in electric-driven system efficiency evidently contradicts the effect of TES. This finding is further explained in **Papers II** and **III**.

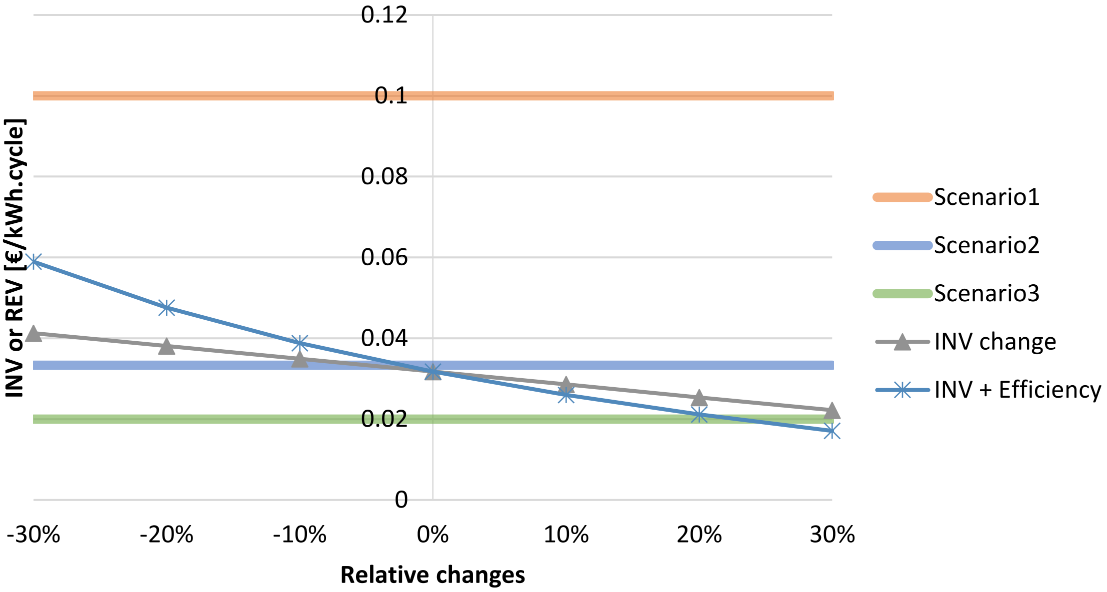


Figure 5.2. Evaluation of standardized investment (INV) and revenue (REV) for the central TES with changes in TES characteristics.

Table 5.1. Parameters about the central water tank and application scenarios in example 1.

Central water tank	Volume	~100 m^3
	Investment	800 €/m^3
	Density	58.3 kWh/m^3
	Full-load cycle	60/year
Application scenarios	Scenario 1	0.1 €/$kWh_{thermal}$, regular DH + free waste heat
	Scenario 2	0.1 €/kWh_e, electricity shifting, $\eta_{p2h} = 1/3$
	Scenario 3	0.1 €/kWh_e, electricity shifting, $\eta_{p2h} = 1/5$

Example 2 refers to the application of building-level or local TES, either as a water-based or PCM-based tank. As the tank size is commonly smaller than 1 m^3, the investment into a local TES is much higher than that of the central TES, as shown in **Table 5.2**. Although having a larger storage density, the investment in the PCM tank is higher than that in the water tank. More detailed analyses and discussions on the two storage types are provided in additional publication VI [30]. By considering the changes in TES units due to their technical development in the future, the standardized investment (INV) is calculated and compared with application benefits, as shown in **Figure 5.3**. Unlike the central unit, the benefits from actively shifting energy can hardly cover the high initial cost of the local TES unit. However, such a conclusion is not a universal answer. If the energy price difference becomes as high as 0.3 €/kWh, the local TES unit might appear as an attractive solution.

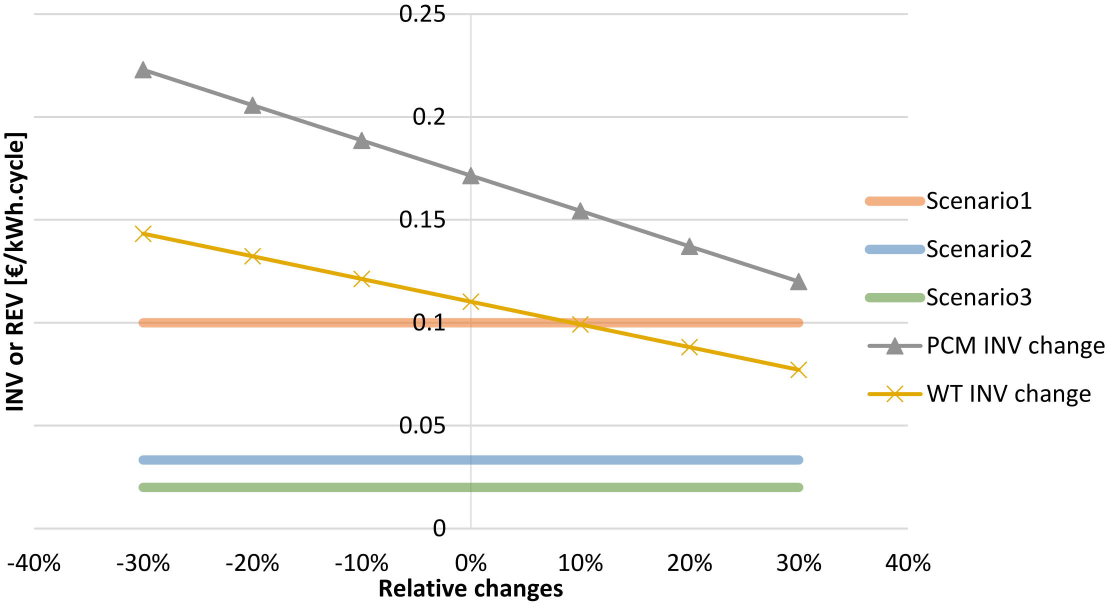


Figure 5.3. Evaluation of standardized investment (INV) and revenue (REV) of local TES for energy shifting.

Table 5.2. Parameters of the local TES in example 2.

	Water tank	Phase change material
Volume	<1 m^3	
Investment	2,500 €/m^3	4,000 €/m^3
Density	47 kWh/m^3	91 kWh/m^3
Full-load cycle	60/year	

Example 3, as shown in **Figure 5.4**, describes three typical scenarios of power shifting benefit compared with the standardized investment for WT. Different investment costs for peak facilities are converted to the annualized unit cycle cost. The worst case in terms of TES utilization, that only one cycle is used a year, is considered. The results show that even with the cheapest power cost, the peak shifting benefit of local TES can apparently cover the relatively high initial TES cost. The power shifting benefit is more attractive than the energy shifting benefit explained in the above two examples. The conclusion is in line with the roadmap study on TES applications, presented in the appended **Paper I**. Therefore, the purpose of this chapter is not to give certain answers to the TES application but to provide an evaluation methodology that works in a changing environment.

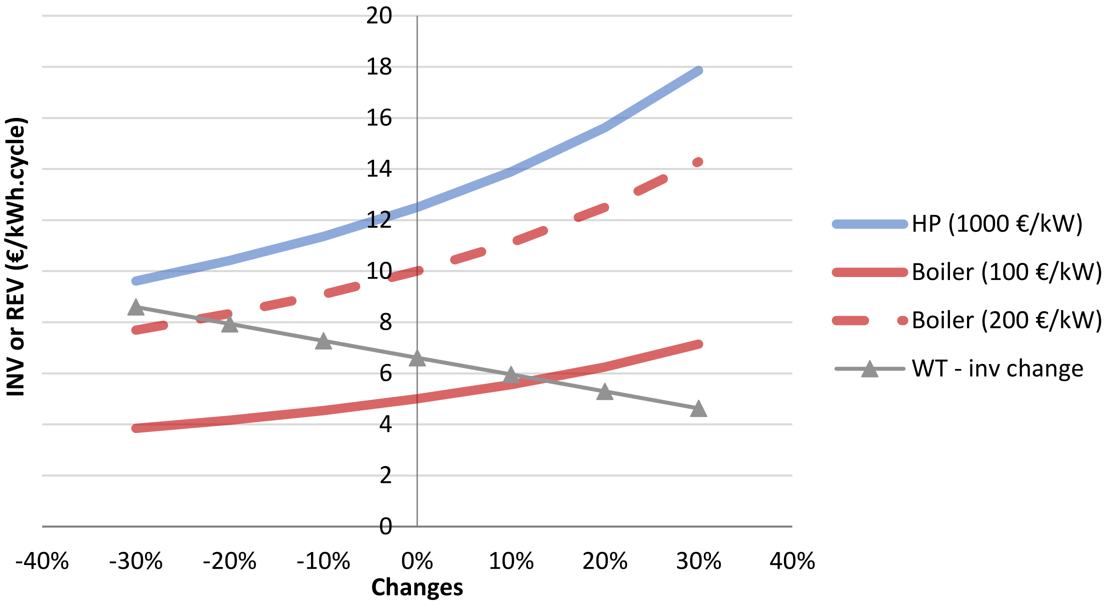


Figure 5.4. Evaluation of standardized investment (INV) and revenue (REV) of local TES for power shifting.

6 Conclusions and future research work

This thesis aims to identify the optimal planning of the different DHC systems with future challenges and changes. Therefore, a generalized methodological framework combining energy system optimization with stochastic simulations, uncertainty analysis, and sensitivity assessment is developed. In addition, the planning of TES units and their roles in future DHC systems is investigated using the proposed evaluation method. Based on the key findings, the practical potential of the novel 5GDHC system in the European building stock is further clarified using GIS-based methods. This thesis combines hypothetical studies and practical implementations. The major conclusions and generic insights based on this summary and the appended papers are presented in **Chapter 6.1**. **Chapter 6.2** clarifies the limitations of the current work, and **Chapter 6.3** indicates the recommendations for future research.

6.1 Conclusion

According to the uncertainty analysis results, the area demand density, DOC, and linear demand density are the most critical deciding factors for the transitions of the 4GDHC system to the ULTDHC, 5GDHC, and individual systems, respectively. As the limits on imported electricity and renewable energy integrations are set, the 5GDHC system has the lowest costs over the investigated cases but cannot reach self-sufficiency due to the difficulty of shifting electricity demand from local equipment. The TES investment also becomes the most critical factor when renewable integration is considered. Compared to DHC systems, the individual system is more sensitive to changes in equipment efficiency and cost. The preferred future conditions and hindering factors for different DHC systems are summarized in the roadmap *via* proposed KPIs clarifying the future focus area for DHC design.

The database containing the geographical information of hectare-level units is used herein to identify the potential of the 5GDHC system. The overlapping heating and cooling demands and demand densities are calculated and applied as criteria to assess feasibility. Most units in the building stock of 2016 have DOC smaller than 0.1, meaning they are unsuitable for the application of the 5GDHC system. Less than 0.1% of the building stock has the potential of the energy-efficient 5GDHC system. Moreover, despite the future decrease of heating demand and the increase of cooling demand due to climate changes and building renovations, the overlapping demand is slightly increased by around 4%, leading to limited additional application potentials of 5GDHC. Therefore, even though the 5GDHC system is an attractive solution for urban centers, its role in the existing building stock is limited.

The optimal applications of TES units along with the transitions of DHC systems have been investigated in appended **Papers I–IV**. However, the acquired benefits of TES have shown significant variations due to the different applied scenarios and systems. A simplified methodology is proposed to solve this puzzle, which can evaluate the applications of TES under different scenarios. Herein, the effectiveness of the proposed method is explained through three typical cases. It is found that the flexibility provided by the TES is limited in DHC systems with lower water temperature and higher efficiency, making the synergy between electricity and heat difficult to achieve. The main reasons behind this are the high power-to-heat ratio and reduced heat storage density. Considering these factors, the proposed method reveals that the effective working storage capacity is only a small part of the overall TES capacity. Moreover, peak power shifting is the primary economic motivation for building-level local TES. However, the current benefit from energy shifting can hardly cover the high initial investment for local TES.

6.2 Limitations

This thesis has explored the sensitive factors of energy system transition under four different objectives. With growing calls for carbon emission reduction and evolving policies and markets for RE, there will be more diverse objectives for energy system design. For example, some urban districts might have the target of net-zero energy, in which the electricity production by local RE is larger than the imported electricity from the grid. The security of energy supply and the self-sufficiency of urban districts attract increasing attention with the changing global politics and energy prices. Such a target calls for a resilient design for the DHC systems and energy storage units. The sensitive factors under these future objectives require further investigations to provide decision makers with more robust suggestions.

The methodologies and results of the research work on the 5GDHC potential can only be used for top-level planning and analysis of regional trends. Bottom-level information, such as building characteristics, is needed for a detailed design of the 5GDHC system in specific cases. Besides, although the process cooling has an important role in the 5GDHC system, it is hard to provide convincing data on its potential from the bottom level. Therefore, this study has used empirical values from various building typologies [74,75]. A special commercial area can have different process cooling demands; thus, the overlapping potential is improperly assessed. However, the analyzed process cooling demand has been cross-checked with the aggregated demand at country levels, ensuring the results are convincing from a general view.

6.3 Future work

Herein, the uncertainties identified when planning the DHC systems are investigated using MC methods. During the operation stage, the input parameters, such as weather conditions and forecasted energy prices, are known for each simulation run. This method is noted as a deterministic design process. However, this is not the case for real DHC systems. Various types of uncertainties are associated with the practical operation of DHC systems. For example, the real power production from RE sources can deviate from the forecasted values and influence energy prices. Therefore, the planned day-ahead operation schemes are not the optimal solution. The operational uncertainties and their impact on the choice of the DHC system in the future shall be further investigated. Similar issues in the microgrid and electricity sectors have already been addressed [82,83]. The findings of this work provide a strong knowledge basis on the evolving system performance under uncertainties and future changes. The dynamic operational uncertainties can be addressed combined with bottom-level control details (e.g., hybrid model predictive control), and the more robust performance of DHC systems can be assured. Such research direction has also been highlighted in a recent literature review on 5GDHC [84].

Based on the analysis of TES applications, this thesis has clarified the limited roles of sensible TES in future DHC systems because the storage density is reduced with low-temperature ranges. However, from the current market data, the large-scale practical application of the PCM unit remains limited owing to high initial investment and issues with its long-term performance [85]. At the planning level, considering up-to-date technological development, the evaluation of novel TES units to identify appropriate application scenarios is promising. Such an evaluation can be performed based on the methods developed in this work. Furthermore, the development of TES technologies suitable for future low-temperature applications is an attractive direction at the bottom level. Recent years have witnessed progress in the absorption storage system based on the enthalpy during the thermochemical reaction. An energy density of approximately 180 kWh/m^3 can be achieved in household applications [86]. Such absorption storage unit is considered a possible space-saving solution to replace sensible water tanks for seasonal storage purposes. However, this technology remains within lab development, which requires much work.

References

[1] European Commission. Eurostat - Statistics database 2021. http://ec.europa.eu/eurostat.

[2] European Commission. Energy and the Green Deal 2020. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/energy-and-green-deal_en (accessed April 7, 2022).

[3] Lund H, Werner S, Wiltshire R, Svendsen S, Eric J, Hvelplund F, et al. 4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. https://doi.org/10.1016/j.energy.2014.02.089.

[4] Lund H, Østergaard PA, Chang M, Werner S, Svendsen S, Sorknæs P, et al. The status of 4th generation district heating: Research and results. Energy 2018;164:147–59. https://doi.org/10.1016/j.energy.2018.08.206.

[5] Averfalk H, Benakopoulus T, Best I, Dammel F, Engel C, Geyer R, et al. Low-Temperature District Heating Implementation Guidebook. IEA DHC Annex TS2 Implement 2021:201.

[6] Yang X, Li H, Svendsen S. Evaluations of different domestic hot water preparing methods with ultra-low-temperature district heating. Energy 2016;109:248–59. https://doi.org/10.1016/j.energy.2016.04.109.

[7] Ommen T, Thorsen JE, Markussen WB, Elmegaard B. Performance of ultra low temperature district heating systems with utility plant and booster heat pumps. Energy 2017;137:544–55. https://doi.org/10.1016/j.energy.2017.05.165.

[8] Buffa S, Cozzini M, D’Antoni M, Baratieri M, Fedrizzi R. 5th generation district heating and cooling systems: A review of existing cases in Europe. Renew Sustain Energy Rev 2019;104:504–22. https://doi.org/10.1016/j.rser.2018.12.059.

[9] Wirtz M, Kivilip L, Remmen P, Müller D. 5th Generation District Heating: A novel design approach based on mathematical optimization. Appl Energy 2020;260:114158. https://doi.org/10.1016/j.apenergy.2019.114158.

[10] Wirtz M, Kivilip L, Remmen P, Müller D. Quantifying Demand Balancing in Bidirectional Low Temperature Networks. Energy Build 2020;224:110245. https://doi.org/10.1016/j.enbuild.2020.110245.

[11] Pellegrini M, Bianchini A. The innovative concept of cold district heating networks: A literature review. Energies 2018;11. https://doi.org/10.3390/en11010236.

[12] Larsen MAD, Petrović S, Radoszynski AM, McKenna R, Balyk O. Climate change impacts on trends and extremes in future heating and cooling demands over Europe. Energy Build 2020;226. https://doi.org/10.1016/j.enbuild.2020.110397.

[13] Kan X, Hedenus F, Reichenberg L. The cost of a future low-carbon electricity system without nuclear power – the case of Sweden. Energy 2020;195:117015. https://doi.org/10.1016/j.energy.2020.117015.

[14] Nik VM, Mata E, Sasic Kalagasidis A, Scartezzini JL. Effective and robust energy retrofitting measures for future climatic conditions - Reduced heating demand of Swedish households. Energy Build 2016;121:176–87. https://doi.org/10.1016/j.enbuild.2016.03.044.

[15] Zhang Y, Johansson P, Sasic Kalagasidis A Applicability of thermal energy storage in future low-temperature district heating systems – Case study using multi-scenario analysis. Energy Convers Manag 2021;244. https://doi.org/10.1016/j.enconman.2021.114518.

[16] Lund H. Renewable heating strategies and their consequences for storage and grid infrastructures comparing a smart grid to a smart energy systems approach. Energy 2018;151:94–102. https://doi.org/10.1016/j.energy.2018.03.010.

[17] Gadd H, Werner S. Thermal energy storage systems for district heating and cooling. Woodhead Publishing Limited; 2015. https://doi.org/10.1533/9781782420965.4.467.

[18] Prasanna A, Dorer V, Vetterli N. Optimisation of a district energy system with a low temperature network. Energy 2017;137:632–48. https://doi.org/10.1016/j.energy.2017.03.137.

[19] Bünning F, Wetter M, Fuchs M, Müller D. Bidirectional low temperature district energy systems with agent-based control: Performance comparison and operation optimization. Appl Energy 2018;209:502–15. https://doi.org/10.1016/j.apenergy.2017.10.072.

[20] Lindhe J, Javed S, Johansson D, Bagge H. A review of the current status and development of 5GDHC and characterization of a novel shared energy system. Sci Technol Built Environ 2022;28:595–609. https://doi.org/10.1080/23744731.2022.2057111.

[21] Millar MA, Elrick B, Jones G, Yu Z, Burnside NM. Roadblocks to low temperature district heating. Energies 2020;13. https://doi.org/10.3390/en13225893.

[22] Allen A, Henze G, Baker K, Pavlak G. Evaluation of low-exergy heating and cooling systems and topology optimization for deep energy savings at the urban district level. Energy Convers Manag 2020;222:113106. https://doi.org/10.1016/j.enconman.2020.113106.

[23] Zhang Y, Johansson P, Sasic Kalagasidis A. Assessment of district heating and cooling systems transition with respect to future changes in demand profiles and renewable energy supplies. Energy Convers Manag 2022;268:116038. https://doi.org/10.1016/j.enconman.2022.116038.

[24] Gudmundsson O, Schmidt RR, Dyrelund A, Thorsen JE. Economic comparison of 4GDH and 5GDH systems – Using a case study. Energy 2022;238:121613. https://doi.org/10.1016/j.energy.2021.121613.

[25] MacDonald I, Strachan P. Practical application of uncertainty analysis. Energy Build 2001;33:219–27. https://doi.org/10.1016/S0378-7788(00)00085-2.

[26] Groen EA, Bokkers EAM, Heijungs R, de Boer IJM. Methods for global sensitivity analysis in life cycle assessment. Int J Life Cycle Assess 2017;22:1125–37. https://doi.org/10.1007/s11367-016-1217-3.

[27] Mavromatidis G, Orehounig K, Carmeliet J. Uncertainty and global sensitivity analysis for the optimal design of distributed energy systems. Appl Energy 2018;214:219–38. https://doi.org/10.1016/j.apenergy.2018.01.062.

[28] Petkov I, Gabrielli P. Power-to-hydrogen as seasonal energy storage: an uncertainty analysis for optimal design of low-carbon multi-energy systems. Appl Energy 2020;274:115197. https://doi.org/10.1016/j.apenergy.2020.115197.

[29] Testi D, Urbanucci L, Giola C, Schito E, Conti P. Stochastic optimal integration of decentralized heat pumps in a smart thermal and electric micro-grid. Energy Convers Manag

2020;210:112734. https://doi.org/10.1016/j.enconman.2020.112734.

[30] Zhang Y, Johansson P, Sasic Kalagasidis A Techno-economic assessment of thermal energy storage technologies for demand-side management in low-temperature individual heating systems. Energy 2021;236:121496. https://doi.org/https://doi.org/10.1016/j.energy.2021.121496.

[31] Zhang Y, Johansson P, Sasic Kalagasidis A. Feasibilities of utilizing thermal inertia of district heating networks to improve system flexibility. Appl Therm Eng 2022;213:118813. https://doi.org/10.1016/j.applthermaleng.2022.118813.

[32] Jangsten M, Filipsson P, Lindholm T, Dalenbäck JO. High Temperature District Cooling: Challenges and Possibilities Based on an Existing District Cooling System and its Connected Buildings. Energy 2020;199. https://doi.org/10.1016/j.energy.2020.117407.

[33] Vivian J, Emmi G, Zarrella A, Jobard X, Pietruschka D, De Carli M. Evaluating the cost of heat for end users in ultra low temperature district heating networks with booster heat pumps. Energy 2018;153:788–800. https://doi.org/10.1016/j.energy.2018.04.081.

[34] Wirtz M, Neumaier L, Remmen P, Müller D. Temperature control in 5th generation district heating and cooling networks: An MILP-based operation optimization. Appl Energy 2021;288:116608. https://doi.org/10.1016/j.apenergy.2021.116608.

[35] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Energy storage and smart energy systems. Energy 2017;137:556–65. https://doi.org/10.1016/j.energy.2017.05.123.

[36] Åberg M, Widén J, Henning D. Sensitivity of district heating system operation to heat demand reductions and electricity price variations: A Swedish example. Energy 2012;41:525–40. https://doi.org/10.1016/j.energy.2012.02.034.

[37] Hast A, Rinne S, Syri S, Kiviluoma J. The role of heat storages in facilitating the adaptation of district heating systems to large amount of variable renewable electricity. Energy 2017;137:775–88. https://doi.org/10.1016/j.energy.2017.05.113.

[38] Kontu K, Rinne S, Junnila S. Introducing modern heat pumps to existing district heating systems – Global lessons from viable decarbonizing of district heating in Finland. Energy 2019;166:862–70. https://doi.org/10.1016/j.energy.2018.10.077.

[39] Romanchenko D, Odenberger M, Göransson L, Johnsson F. Impact of electricity price fluctuations on the operation of district heating systems: A case study of district heating in GÖteborg, Sweden. Appl Energy 2017;204:16–30. https://doi.org/10.1016/j.apenergy.2017.06.092.

[40] Quirosa G, Torres M, Chacartegui R. Analysis of the integration of photovoltaic excess into a 5th generation district heating and cooling system for network energy storage. Energy 2021;239:122202. https://doi.org/10.1016/j.energy.2021.122202.

[41] Edtmayer H, Nageler P, Heimrath R, Mach T, Hochenauer C. Investigation on sector coupling potentials of a 5th generation district heating and cooling network. Energy 2021;230:120836. https://doi.org/10.1016/j.energy.2021.120836.

[42] Vivian J, Chinello M, Zarrella A, De Carli M. Investigation on Individual and Collective PV Self-Consumption for a Fifth Generation District Heating Network. Energies 2022;15. https://doi.org/10.3390/en15031022.

[43] Andrić I, Pina A, Ferrão P, Fournier J, Lacarrière B, Le Corre O. The impact of climate change on building heat demand in different climate types. Energy Build 2017;149:225–34. https://doi.org/10.1016/j.enbuild.2017.05.047.

[44] Nik VM, Sasic Kalagasidis A. Impact study of the climate change on the energy performance of the building stock in Stockholm considering four climate uncertainties. Build Environ 2013;60:291–304. https://doi.org/10.1016/j.buildenv.2012.11.005.

[45] IPCC. The Intergovernmental Panel on Climate Change 2022. https://www.ipcc.ch/ (accessed June 1, 2022).

[46] Savvidou G, Nykvist B. Heat demand in the Swedish residential building stock - pathways on demand reduction potential based on socio-technical analysis. Energy Policy 2020;144. https://doi.org/10.1016/j.enpol.2020.111679.

[47] European Commission. A Renovation Wave for Europe – Greening our buildings, creating jobs, improving lives 2020. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en.

[48] Nguyen T, Gustavsson L, Dodoo A, Tettey UYA. Implications of supplying district heat to a new urban residential area in Sweden. Energy 2020;194:116876. https://doi.org/10.1016/j.energy.2019.116876.

[49] Lund R, Østergaard DS, Yang X, Mathiesen BV. Comparison of low-temperature district heating concepts in a long-term energy system perspective. Int J Sustain Energy Plan Manag 2017;12:5–18. https://doi.org/10.5278/ijsepm.2017.12.2.

[50] Meesenburg W, Ommen T, Thorsen JE, Elmegaard B. Economic feasibility of ultra-low temperature district heating systems in newly built areas supplied by renewable energy. Energy 2020;191:116496. https://doi.org/10.1016/j.energy.2019.116496.

[51] Saltelli A, Ratto M, Andres T, Campolongo F, Cariboni J, Gatelli D, et al. Global sensitivity analysis: the primer. John Wiley & Sons; 2008.

[52] Danish Energy Agency and Energinet. Technology Data - Energy Plants for Electricity and District heating generation First 2022.

[53] Madonna F, Bazzocchi F. Annual performances of reversible air-to-water heat pumps in small residential buildings. Energy Build 2013;65:299–309. https://doi.org/10.1016/j.enbuild.2013.06.016.

[54] Reinholdt L, Kristófersson J, Zühlsdorf B, Elmegaard B, Jensen J, Ommen T, et al. Heat pump COP, part 1: Generalized method for screening of system integration potentials. Refrig Sci Technol 2018;2018-June:1207–13. https://doi.org/10.18462/iir.gl.2018.1380.

[55] R LA, A J-W, M V, B S, D M, M J, et al. ETRI 2014 - Energy Technology Reference Indicator projections for 2010-2050. Luxembourg (Luxembourg): Publications Office of the European Union; 2014. https://doi.org/10.2790/057687.

[56] Danish Energy Agency and Energinet. Technology Data – Energy storage. 2018.

[57] Göransson L, Goop J, Unger T, Odenberger M, Johnsson F. Linkages between demand-side management and congestion in the European electricity transmission system. Energy 2014;69:860–72. https://doi.org/10.1016/j.energy.2014.03.083.

[58] Romanchenko D, Kensby J, Odenberger M, Johnsson F. Thermal energy storage in district heating: Centralised storage vs. storage in thermal inertia of buildings. Energy Convers Manag 2018;162:26–38. https://doi.org/10.1016/j.enconman.2018.01.068.

[59] Jordan U, Vajen K. Realistic domestic hot-water profiles in different time scales. Rep Sol Heat Cool Progr Int Energy Agency (IEA-SHC)Task 2001;26:1–18.

[60] Braas H, Jordan U, Best I, Orozaliev J, Vajen K. District heating load profiles for domestic hot water preparation with realistic simultaneity using DHWcalc and TRNSYS. Energy 2020;201:117552. https://doi.org/10.1016/j.energy.2020.117552.

[61] Hotmaps 2022. https://www.hotmaps.eu/map (accessed October 1, 2022).

[62] The Hotmaps project. Hotmaps – Heating and Cooling Open Source Tool for Mapping and Planning of Energy Systems. 2019.

[63] European Commission. Population and housing census 2011. https://ec.europa.eu/eurostat/web/population-demography/population-housing-censuses.

[64] European Environmental Agency. Corine Land Cover 2006 2006. https://www.eea.europa.eu/data-and-maps/data/clc-2006-raster-4.

[65] Joint Research Centre. European Settlement Map 2016. https://land.copernicus.eu/pan-european/GHSL/european-settlement-map.

[66] Joint Research Centre. GHS-BUILT R2018A - GHS built-up grid, derived from Landsat, multitemporal 2015. https://data.jrc.ec.europa.eu/dataset/jrc-ghsl-10007.

[67] Werner S. European space cooling demands. Energy 2016;110:148–56. https://doi.org/10.1016/j.energy.2015.11.028.

[68] Sachs J, Moya D, Giarola S, Hawkes A. Clustered spatially and temporally resolved global heat and cooling energy demand in the residential sector. Appl Energy 2019;250:48–62. https://doi.org/10.1016/j.apenergy.2019.05.011.

[69] Birchall S, Wallis I, Churcher D, Pezzutto S, Fedrizzi R, Causse E. D2. 1a Survey on the energy needs and architectural features of the EU building stock. EC FP7 Proj INSPiRe, Grant Agreem 2014.

[70] Werner S. The European Heat Market. Final Report. Euroheat & Power 2016.

[71] ODYSSEE-MURE. ODYSSEE database on energy efficiency data & indicators 2017. https://www.indicators.odyssee-mure.eu/energy-efficiency-database.html.

[72] Giorgi F, Gutowski WJ. Regional Dynamical Downscaling and the CORDEX Initiative. Annu Rev Environ Resour 2015;40:467–90. https://doi.org/10.1146/annurev-environ-102014-021217.

[73] Deep Renovation: Shifting from exception to standard practice in EU Policy. 2021.

[74] Nicolas PG, Konstaninos V, Anna K-R, Antonio MRJ, Alicia PL. Heat and Cooling Demand and Market Perspective, Report EUR 25381 EN. 2012. https://doi.org/10.2790/56532.

[75] Fleiter T, Steinbach J, Ragwitz M. Mapping and analyses of the current and future (2020 - 2030)

heating/cooling fuel deployment (fossil/renewables) - Work package 1: Final energy consumption for the year 2012. Eur Comm under Contract N°ENER/C2/2014-641 2016:1–141.

[76] Zarin Pass R, Wetter M, Piette MA. A thermodynamic analysis of a novel bidirectional district heating and cooling network. Energy 2018;144:20–30. https://doi.org/10.1016/j.energy.2017.11.122.

[77] Nik, Moussavi V. Hygrothermal Simulations of Buildings Concerning Uncertainties of the Future Climate, PhD. Gothenburg, Sweden: Chalmers University of Technology; 2012.

[78] Spinoni J, Vogt J, Barbosa P. European degree-day climatologies and trends for the period 1951-2011. Int J Climatol 2015;35:25–36. https://doi.org/10.1002/joc.3959.

[79] European Commission. Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU Final report 2019.

[80] Schütz T, Streblow R, Müller D. A comparison of thermal energy storage models for building energy system optimization. Energy Build 2015;93:23–31. https://doi.org/10.1016/j.enbuild.2015.02.031.

[81] Campos Celador A, Odriozola M, Sala JM. Implications of the modelling of stratified hot water storage tanks in the simulation of CHP plants. Energy Convers Manag 2011;52:3018–26. https://doi.org/10.1016/j.enconman.2011.04.015.

[82] Jin M, Feng W, Liu P, Marnay C, Spanos C. MOD-DR: Microgrid optimal dispatch with demand response. Appl Energy 2017;187:758–76. https://doi.org/10.1016/j.apenergy.2016.11.093.

[83] Hargreaves JJ, Hobbs BF. Commitment and dispatch with uncertain wind generation by dynamic programming. IEEE Trans Sustain Energy 2012;3:724–34. https://doi.org/10.1109/TSTE.2012.2199526.

[84] Gjoka K, Rismanchi B, Crawford RH. Fifth-generation district heating and cooling systems: A review of recent advancements and implementation barriers. Renew Sustain Energy Rev 2023;171:112997. https://doi.org/10.1016/j.rser.2022.112997.

[85] Tan P, Lindberg P, Eichler K, Löveryd P, Johansson P, Kalagasidis AS. Thermal energy storage using phase change materials: Techno-economic evaluation of a cold storage installation in an office building. Appl Energy 2020;276:115433. https://doi.org/10.1016/j.apenergy.2020.115433.

[86] Guelpa E, Verda V. Thermal energy storage in district heating and cooling systems: A review. Appl Energy 2019;252:113474. https://doi.org/10.1016/j.apenergy.2019.113474.

Part II

Appended Papers

Paper I

Applicability of thermal energy storage in future low-temperature district heating systems–Case study using multi-scenario analysis

Yichi Zhang, Pär Johansson, Angela Sasic Kalagasidis

Energy Conversion and Management (2021), 244, 114518

Paper II

Assessment of district heating and cooling systems transition with respect to future changes in demand profiles and renewable energy supplies

Yichi Zhang, Pär Johansson, Angela Sasic Kalagasidis

Energy Conversion and Management (2022), 268, 116038

Paper III

Roadmaps for heating and cooling system transitions seen through uncertainty and sensitivity analysis

Yichi Zhang, Pär Johansson, Angela Sasic Kalagasidis

Submitted to Applied Energy (2023)

Paper IV

Quantifying overlapped heating and cooling demands and the feasibility of bi-directional systems over Europe

Yichi Zhang, Pär Johansson, Angela Sasic Kalagasidis

Submitted to Energy and Buildings (2023)