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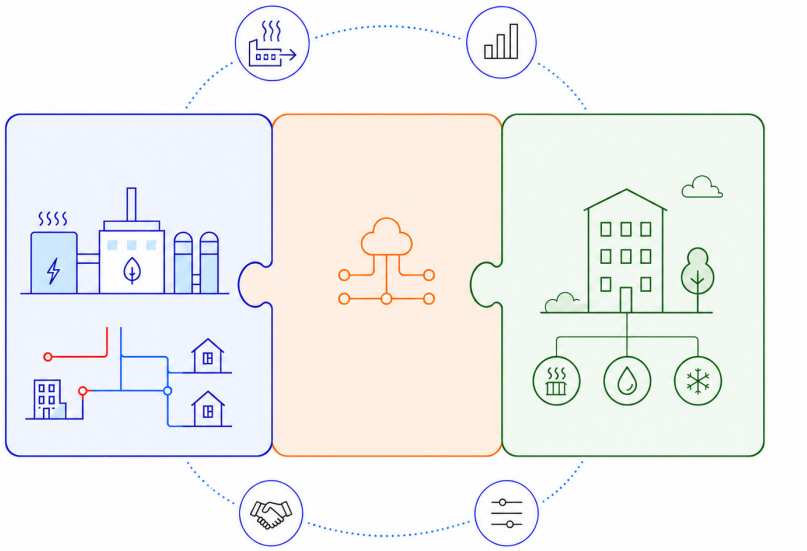

From Silos to Ecosystems? Radical Exploration and Transformation in District Heating

Håkan Knutsson

Halmstad University | School of Business, Innovation and Sustainability
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From Silos to Ecosystems? Radical Exploration and Transformation in District Heating

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Abstract

The energy transition is creating new challenges for district heating (DH) firms. These firms operate capital-intensive infrastructure with long investment cycles and strong requirements for reliability, while at the same time facing pressure from decarbonisation, electrification, digitalisation, new customer demands, and increasing competition from alternative heating solutions such as heat pumps. Historically, innovation in DH has mainly focused on improving existing production and distribution systems. This production-oriented and incremental innovation logic may become insufficient as the energy transition requires DH firms to address increasingly complex problems involving new technologies, customers, and external actors.

Less is known about how incumbent DH firms search for more distant solutions, collaborate with external actors, and reorganise value creation when incremental improvement is no longer sufficient.

The purpose of this doctoral thesis is to understand how innovation in the district heating sector develops under conditions of energy transition. More specifically, the thesis examines how DH firms engage in exploration with external partners, and how such exploration may reconfigure inter-firm relationships and existing value systems.

The thesis comprises a compendium and five papers and uses a predominantly qualitative and exploratory research design. The empirical material includes a structured literature review, workshops, interviews, observations, documentary material, and longitudinal case studies involving DH firms and other actors in several European contexts.

Three major findings emerge from the thesis.

First, innovation in the DH sector remains predominantly incremental and strongly shaped by path dependence. DH firms have developed considerable capabilities for improving production, distribution, fuel use, and operational efficiency within established technological and organisational structures. Long-lived assets, sunk costs, regulatory arrangements, established supplier relationships, and demands for reliability all reinforce this exploitation-oriented logic. These conditions have supported reliable and increasingly low-carbon heat supply, but they also encourage local search around familiar technologies and solutions. Transformation

of the DH firms therefore tends to be gradual, uneven, and selective rather than disruptive.

Second, the empirical cases show that radical exploration in DH takes several distinct forms, depending on technological distance, the actors involved, and how innovation is organised across organisational boundaries. The thesis identifies five patterns of radical exploration, ranging from supplier-led development within the incumbent DH system to customer integration, entrant-led innovation, and emerging ecosystem-based configurations in the production respectively customer sides. Across these patterns, the locus of innovation gradually moves away from the production core of the DH firm toward customers, property owners, technology suppliers, entrants, complementors, and other external actors. The actor leading innovation may therefore also change. Radical exploration is consequently not only a search for new technology; it is also a search for partners, capabilities, and suitable ways of organising collaboration across firms.

Third, the findings show that transformation in heating is increasingly about how value creation is organised, not only about which technology is used. Traditional DH is typically organised as a hierarchy-based value system in which one focal firm controls production, distribution, and the customer interface. Individual heat pumps are more commonly embedded in market-based arrangements, while new combinations of district heating, heat pumps, cooling, storage, digital technologies, and customer-side resources may require more ecosystem-based forms of coordination. Competition in the heating sector can therefore increasingly be understood as competition between alternative value-system configurations. Platform-based ecosystems represent one possible emerging coordination mechanism, although the thesis finds that such configurations are still at an early stage and introduce new challenges related to governance, control, dependency, and value capture.

Overall, the thesis shows that the transformation of district heating is best understood as a gradual reconfiguration of innovation search, actor roles, and value systems. Incumbent DH firms remain strongly rooted in established infrastructure logics, but pressures from electrification, digitalisation, customer integration, and new entrants are expanding the solution landscape. Moving from silos toward more ecosystem-like forms of innovation therefore requires not only new technologies, but also new ways of searching, collaborating, and coordinating value creation across organisational boundaries.

The findings may also inform understanding of innovation and transformation in other mature infrastructure-based utilities characterised by long-lived assets, path dependence, and increasing technological uncertainty.

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Abbreviations and Acronyms

4GDH	4th generation District Heating, low temp.
5GDHC	5th generation District Heating and Cooling.
AI	Artificial Intelligence
CHP	Combined Heat and Power
DC	District Cooling
DH	District Heating
DHC	District Heating and Cooling
ML	Machine Learning
MSP	Multi-Sided-Platform
PSS	Product Service Systems
RQ	Research Question

1. Introduction

This doctoral thesis examines how district heating (DH) firms transform under conditions of accelerating energy transition by engaging in new forms of innovation and external collaboration. DH represents a central component of urban energy systems and is widely regarded as an enabling infrastructure for decarbonising heat supply through the integration of renewable energy and recovered waste heat. At the same time, DH firms operate as incumbent organisations embedded in capital-intensive infrastructures, long investment cycles, and historically stable market arrangements. These characteristics create strong technology path dependencies (Dosi, 1982), shaping how firms search for solutions and limiting their ability to respond rapidly to emerging technological and market pressures. In the context of decarbonisation, electrification, and increasing competition from alternative heating solutions, these historically stable arrangements are increasingly being challenged. DH firms are expected not only to reduce CO_2 emissions, but also to integrate more diverse sources of recovered and heat, lower system temperatures, and interact more closely with customers and external partners (Kristina Lygnerud, Popovic, Schultze, & Støchkel, 2023; Schmidt et al., 2021). As this thesis will show, meeting these expectations requires more than technological change. It also involves new forms of inter-firm coordination, value creation, and innovation search. Yet empirical understanding of how DH firms engage in such processes, particularly through collaboration with external actors, remains limited.

These challenges are not unique to DH firms. Other infrastructure-based utilities and asset-intensive industries face similar pressures as established systems are required to adapt to changing technological, environmental, and societal demands. Water utilities must reduce losses in ageing distribution networks while responding to increasing water scarcity. Sewage systems need to address leakage, stormwater separation, and capacity constraints. Electricity distribution operators face growing challenges in meeting capacity requirements due to changing patterns of local electricity generation, electrification, and consumption. Taken together, these examples indicate that the transformation of DH firms forms part of a broader challenge confronting incumbent infrastructure-based utilities under conditions of transition and increasing uncertainty. These broader pressures are particularly visible in DH, where long-lived infrastructure and historically stable organisational arrangements are increasingly confronted by new technological, market, and policy conditions.

1.1 District Heating – a City Utility Service under pressure

Heating as a thermal process that is a critical component of the European energy consumption, accounting for approximately half of total energy use, primarily for space heating and hot water in buildings (Connolly, Lund, & Mathiesen, 2016). At the same time, the volume of unrecovered industrial waste heat in Europe exceeds the total heat demand of buildings (Persson, Möller, & Werner, 2014). DH systems are uniquely positioned to connect sources of surplus heat with areas of demand, embodying a core principle of the circular economy.

The technical potential of DH is well established. Research has demonstrated how advanced DH systems can increase energy efficiency, support power system integration, and contribute to deep decarbonisation. According to the Heat Roadmap 5 Europe[1], DH could supply more than 50% of Europe's heat demand, in the future. Heat pumps and DH are widely recognised as key technologies in the transition away from fossil fuels (Elavarasan et al., 2022), aligning with the objectives of the EU Green Deal (EUCommission, 2019).

Despite this potential, the transformation and expansion of the DH firms have progressed slowly (Wesche, Negro, Dütschke, Raven, & Hekkert, 2019). DH firms face a combination of interrelated challenges. First, they must preserve and renew assets such as aging production plants and pipe networks—often several decades old—characterised by long but expired depreciation periods and high replacement costs (Hay, Leuteritz, & Morgenthum, 2021; Hay et al., 2023; Vega, Yarahmadi, & Jakubowicz, 2020). Many of the oldest pipes, installed during the 1960s, are located beneath streets in city centres, making replacement costly, disruptive and time-consuming. Second, the DH firms must transform existing DH systems toward lower operating temperatures and integrate new sources of waste heat – a transition commonly framed as fourth-generation district heating, 4GDH (Lund et al., 2018). While DH firms in Northern and Central Europe have successfully shifted from fossil to renewable fuels (Ericsson & Werner, 2016), lowering system temperatures and enabling bidirectional heat flows requires deeper organisational change and closer interaction with customers and heat suppliers, yet in practice only limited improvements have been observed[2]. Achieving lower system temperatures depends heavily on customer-side adaptations, yet DH firms have traditionally maintained limited interaction with their customers. There are also other customer needs that DH firms struggle to satisfy. Demand for cooling is increasing (Ürge-Vorsatz, Cabeza, Serrano, Barreneche, & Petrichenko, 2015), due to climate change, urban heat islands (Stone Jr, 2007), modern insulated

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1 Source: EuroHeat and Power, Heat Road Map 5. A new study by Aalborg University- Towards a sustainable, resilient and competitive heating sector by 2050 - Euroheat & Power

2 Handbok för sänkta fjärrvärmetemperaturer Handbook for lower system temperature.

buildings with large window surfaces, and, not least, rising expectations of personal comfort. The integration of decentralised heating and cooling is addressed through the system configuration commonly referred to as fifth-generation district heating and cooling, or 5GDHC (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019; Lindhe, Javed, Johansson, & Bagge, 2022), although the definition remains contested within the DH research community (Henrik Lund et al., 2021).

Third, DH firms operate urban infrastructure within complex policy and regulatory environments. Depending on the national context, they may operate under regulated monopoly[3] and pricing conditions or compete with alternative heating technologies. The planned phase-out of fossil fuels—particularly natural gas (Braunger, 2023) and its path-dependence—raises fundamental questions about financing, ownership of the DH systems, competition, and customer protection. Often, the same energy company owns the existing gas, electricity and DH networks. The transition between heating systems may therefore have substantial implications for invested capital and the risk of stranded assets. Basically, DH firms, as well as operators of gas and electric networks, strive to reach a temporary monopoly in their geographic domain, a dynamic also observed in many platform-based concepts characterised by network effects (the platform grows stronger with a growing number of subscribers), eventually leading to "winner takes all" (Jia, Cusumano, & Chen, 2019). A market monopoly can be created by market forces or legally founded and protected, with no other choices for the customers. On the other hand, electrification and the rapid diffusion of building-level heat pumps pose a growing competitive threat to DH firms. As customers exit DH systems or use heat pumps in parallel, the financial viability of network-based heat supply is undermined, potentially triggering a downward spiral (Dick Magnusson, 2012; D. Magnusson, 2016; Dick Magnusson & Grundel, 2023) similar to that experienced by other network utilities, such as fixed-line, copper wire telecommunications. The global expansion of electricity generation and electrification through heat pumps may in fact create a market shock for DH, which risks being substituted. There are examples of market shocks in other industries where previously market leading incumbents like Kodak, Nokia, Rank Xerox (Upadhayay, Prajapati, & Alqassimi, 2024) lost their dominance to entrants. This situation is ongoing, where entrant brands of electric vehicles are gaining market dominance, forcing incumbent firms to search and explore external knowledge for new solutions (Tryggvason & Giones, 2025). Even if DH is designated as a substitute for gas, it does not mean that DH is always competitive and the natural choice. External factors like emission fees (ETS) on waste plastics, the Russian aggression on Ukraine causing

[3] DH regulation differs significantly across countries. Swedish DH firms are not legally protected monopolies as in neighbour countries and as in other types of city utilities (water, power distribution).

higher fuel prices, EU restrictions on biomass from forests and uncertain electricity prices are affecting costs and revenues, exacerbating the challenges.

The combination of the three types of challenges, and the emerging threat of increasing competition from heat pumps, is a drastic shift from stable market conditions to increased uncertainty, and conditions not previously experienced by the DH firms. It will be harder, as in the past, rely only on incremental development while managing infrastructure with minimum turn-over of customers. Arguably, it will be an increasingly need to also explore and develop new capabilities and innovations.

The transition literature is rich in addressing this type of challenges and problems around industries in need of change and transformation (Köhler et al., 2019), for instance the effect of path-dependence (Dosi, 1982) explained above. Freeman (1989) linked path dependence to long waves of technological change. As an example, gas and oil infrastructure have had more than a century of waves of improvements but must now be substituted with low carbon alternatives such as DH, introduced broadly about a half century ago, or with heat pumps, introduced broadly in Europe recently[4]. Another stream of literature is looking at socio-technical understanding in multi-level perspectives (Frank W Geels, Sovacool, Schwanen, & Sorrell, 2017), and on the energy transition to low carbon solutions (Di Lucia & Ericsson, 2014; Ericsson & Werner, 2016; F. W. Geels & Johnson, 2018; Köhler et al., 2019). DH systems can be categorised as a Large Technical System (Dick Magnusson & Grundel, 2023), which according to Sovacool, Lovell, and Ting (2018) go through phases of invention, expansion, growth (Hughes, 1987) and later reach maturity, reconfiguration, contestation and eventually stagnation and decline (Dick Magnusson, 2012). This literature provides important explanations of transition pathways and system-level change but offers less detailed insight into how incumbent firms search for alternatives, collaborate with external actors and attempt to move beyond established technological trajectories.

Path-dependence is also related to how individual DH firms are organised and how they deliver value to their customers. The typical value system for DH firms is hierarchy-based, as defined by Jacobides, Cennamo, and Gawer (2018, 2024), where one firm controls the upstream fuel supply, internal heat production, distribution and transfer to the customers. This control tends to lock the DH firm into a silo, complicating their exploration for new solutions and innovations, not sufficiently fit for competition with heat pumps or gas distribution.

Together, these developments represent a shift from historically stable conditions to a state of heightened uncertainty. DH firms will have problems to rely solely on

[4] In Sweden, large as well as small heat pumps were introduced in the 1980s on a broad scale (Johansson, 2017).

incremental improvements and operational efficiency. Increasingly, they must also explore new technologies, organisational forms, and modes of value creation.

1.2 Research problem

These sector-specific challenges provide the empirical context for a broader innovation problem: how incumbent infrastructure-based firms can move beyond established trajectories and engage in exploration under conditions of increasing uncertainty.

1.2.1 The innovation dilemma: exploitation versus exploration

The energy transition confronts incumbent infrastructure-based firms with a fundamental innovation dilemma: how to ensure reliable and efficient operation of existing systems while simultaneously developing new solutions under conditions of uncertainty. This dilemma has been extensively discussed in the innovation literature, especially as a tension between exploitation and exploration (Lavie, 2006; Lavie, Stettner, & Tushman, 2010; March, 1991; Xing, Chin, Huang, Perano, & Temperini, 2024), but recently also in a broader perspective as paradox theory (W. K. Smith & Lewis, 2011). Such dilemmas are common in innovation and business, e.g. stability vs. change, short-term performance vs. long term growth, individual freedom vs. collective control, centralisation vs. decentralisation, profit vs. purpose (sustainability), as described by W. Smith and Lewis (2022). A notable paradox in the energy sector is the regulation/monopoly vs. growth/innovation/scalability.

While exploitation focuses on efficiency, refinement, and incremental improvement based on existing resources and routines, exploration involves experimentation and search for novel and potentially disruptive alternatives. Empirical research shows that incumbent firms—particularly in asset-intensive and regulated industries—systematically privilege exploitation over exploration (Lavie & Rosenkopf, 2006; Lavie et al., 2010). The balance between exploitation and exploration is influenced by contextual factors such as regulation, competitive intensity, ownership structures and opportunities for geographical or organisational scaling. Historically, many DH firms have operated under municipal ownership and within locally protected or weakly competitive markets, conditions that may reduce incentives for exploratory innovation.

In particular, long asset lifetimes, high sunk costs, and risk-averse performance metrics reinforce incremental innovation and make radical exploration difficult to justify organisationally.

1.2.2 Innovation and search

Research and Development (R&D) work, in terms of breakthrough inventions leading to innovations, is the core of Schumpeterian entrepreneurial action and creative destruction (Aghion, Blundell, Griffith, Howitt, & Prantl, 2009; Ahuja, Lampert, & Tandon, 2008; Schumpeter, 2008). The literature has used inventions in two distinct perspectives (Jung & Lee, 2016). The first refers to path-breaking discontinuities (Henderson & Clark, 1990), which are often external to the firm, hence making incumbent technology obsolete (Lavie et al., 2010). The second strand of the literature focuses on the usefulness of an invention for subsequent developments and innovations (Singh & Fleming, 2010), a new capital resource (Lachmann, 1956), which in the heating sector can be represented by the diffusion of heat pumps sold directly to building owners, substituting gas or oil boilers or DH.

In this thesis, search refers to the process through which firms identify, develop, and evaluate possible solutions to innovation problems (Laursen, 2012). Search may remain close to existing knowledge, technologies, routines, and relationships, or extend toward more distant alternatives. Local search builds mainly on accumulated experience and established capabilities, whereas more distant search involves unfamiliar knowledge, technologies, or actors and therefore greater uncertainty (Gavetti & Levinthal, 2000; Levitt & March, 1988). Search is thus not limited to finding a technology; it also concerns where firms look for knowledge, which actors they involve, and how alternative solutions are evaluated and combined.

Exploration and exploitation can be understood as different forms of search involving problem-solving, knowledge development, organisational learning (Argote, Lee, & Park, 2021), including knowledge recombination (Xiao, Makhija, & Karim, 2022) and knowledge transfer (Argote, 2024). Firms focused on exploitation tend to stay with local search, while firms more prone to exploration are stretching to distant search.

A central insight from organisational learning and innovation research is that firms tend to rely on exploitation based on existing knowledge, routines, and relationships (Lavie & Rosenkopf, 2006; Levitt & March, 1988; Rosenkopf & Nerkar, 2001). Local search is efficient when problems are well understood and environments are stable. However, it risks organisational myopia by reinforcing attention to familiar experience and thereby overlooking distant alternatives, longer-term consequences, and unsuccessful experience (Levinthal & March, 1993).

Exploration, by contrast, typically requires distant search in the sense of new technologies and external collaboration. This implies novel and potentially uncertain knowledge and relationships across technological, organisational, or

market boundaries, often with weak feedback signals and delayed returns (Gavetti & Levinthal, 2000). Literature indicates that it is not only organisational and environmental conditions that drive firms' willingness to explore versus exploit (Duysters, Lavie, Sabidussi, & Stettner, 2020). Firms follow alliance partners and competitors but can also diverge from competitors if the proximity is too close.

Early technological and organisational choices shape subsequent search behaviour by constraining what firms perceive as feasible or legitimate options (Nelson & Winter, 1982), which creates path dependence (Dosi, 1982).

1.2.3 Path dependence and constraints in infrastructure-based industries

In infrastructure-based utilities, such as gas, electricity, and district heating, path dependence is particularly strong because of legacy assets, long investment cycles, system interdependencies, and regulatory frameworks that often reward stability rather than experimentation. Early technological and organisational choices therefore continue to shape what firms perceive as feasible, legitimate, and economically attractive alternatives.

DH firms exemplify these conditions. Historically, innovation in the sector has focused mainly on improving fuel efficiency, environmental performance, and system operation. Such trajectories reflect exploitation-oriented search and dependence on established suppliers (Pavitt, 1984). They have generated substantial improvements in reliability and environmental performance, but they may also reduce incentives for more exploratory investments and reinforce established technological and organisational trajectories.

The energy transition is changing the nature of the problems facing DH firms. Decarbonisation, electrification, competition from building-level heat pumps, integration of new sources of surplus heat, increasing demand for cooling, and closer interaction with customers require combinations of technologies, services, and organisational arrangements that extend beyond the traditional production-oriented logic of DH. These challenges increasingly involve several interdependent parts of the system and cannot always be addressed through incremental improvement of individual components.

Traditional DH firms, like firms in other capital-intensive infrastructure sectors, tend to search within a relatively limited solution landscape (Baumann, Schmidt, & Stieglitz, 2019; Ganco, Kapoor, & Lee, 2020). Search is commonly concentrated within the internal organisation and among established suppliers, with less attention directed toward customers, new entrants, and other potential external partners. This tendency is reinforced by the hierarchy-based value system typical of DH, in which one organisation controls production, distribution, and the customer interface (Jacobides et al., 2018, 2024). While this configuration supports

reliability, coordination, and operational efficiency, it may also narrow the range of technologies, knowledge, and alternative solutions considered. Under conditions of technological and market change, such restricted search increases the risk of remaining close to familiar local optima, reinforces organisational myopia, and can limit both upstream integration with new providers of surplus heat and downstream integration with customers and their building-level energy systems.

The fragmented structure of the DH sector further reinforces these constraints. Many DH firms are relatively small and locally embedded, which limits the resources available for R&D and the accumulation of specialised innovation capabilities. Fragmentation also makes it more difficult to scale and diffuse exploratory initiatives across the sector. As a result, radical exploration may depend increasingly on suppliers, consultants, research programmes, customers, or other external actors rather than being organised entirely within individual DH firms.

Many of the emerging challenges are also highly interdependent and difficult to decompose into independent sub-problems (Baumann & Siggelkow, 2013; Ganco et al., 2020; Gavetti & Levinthal, 2000). Integrating new heat sources, developing cooling services, combining electrification with existing networks, or increasing customer-side integration may require simultaneous changes in technologies, organisational arrangements, and actor relationships. Such complex non-decomposable problems are poorly suited to local, experiential search because changes in one part of the system may affect several others.

Addressing these problems may therefore require DH firms not only to search more widely, but also to organise problem-solving and innovation across organisational boundaries. Studies of other industries, including infrastructure-based sectors such as telecommunications, electricity, and mobility, suggest that periods of technological and market turbulence can trigger more open and collaborative forms of innovation (Adner, 2006; Cusumano, Gawer, & Yoffie, 2019). As established technological and organisational arrangements become less sufficient, firms may increasingly depend on complementary knowledge and resources distributed across multiple actors. Innovation may consequently shift from being organised mainly within vertically integrated firms and established supply chains toward networks or ecosystems of interdependent actors (Wang, Zheng, Zhang, Kumar, & Srivastava, 2024).

This creates a particular challenge for incumbent DH firms: established structures support reliability and efficient exploitation, while emerging and increasingly complex problems require broader search, new external relationships, and potentially new forms of coordination. Understanding how firms manage this tension provides the basis for the research gap developed in the following section.

1.2.4 Research gap

While the broader innovation literature provides strong theoretical explanations for why incumbent firms tend to favour exploitation and local search, less is known about how infrastructure-based firms organise more exploratory search when established technological and organisational trajectories become insufficient. This is particularly relevant in mature infrastructure sectors, where firms must continue to operate reliable existing systems while simultaneously searching for solutions to new and increasingly complex problems.

The DH literature increasingly highlights the need for new business models, closer customer relationships, and new contractual and collaborative arrangements (K. Lygnerud, 2018; Kristina Lygnerud, Ottosson, Kensby, & Johansson, 2021; Kristina Lygnerud et al., 2023). However, it provides more limited insight into the search processes through which such innovations emerge: where DH firms look for alternative solutions, how far they search beyond existing technologies and routines, which external actors they involve, and how these actors become integrated into innovation processes. In particular, relatively little is known about how search changes when familiar suppliers, technologies, and accumulated experience no longer provide sufficient solutions.

In this thesis, search beyond both established technological knowledge and organisational boundaries is conceptualised as radical exploration (Rosenkopf & Nerkar, 2001). Such exploration differs from the predominantly local and experiential search associated with exploitation because it requires firms to engage with unfamiliar technologies, knowledge, and external actors under conditions of greater uncertainty. Although the innovation, search, ecosystem, and platform literatures provide conceptual tools for analysing these processes (Adner, 2017; Jacobides et al., 2018, 2024; Laursen, 2012), they have been applied less extensively to mature, infrastructure-based utilities such as DH (Chen, Chen, & Lan, 2016; Greco, Locatelli, & Lisi, 2017).

A further gap concerns the organisational consequences of external search. Radical exploration is not only a question of identifying new technologies. As innovation increasingly involves suppliers, customers, entrants, complementors, and other partners, firms must also determine how knowledge and complementary resources are coordinated across organisational boundaries. Existing value-system configurations may enable some forms of collaboration while constraining others. Exploration may therefore involve changes not only in technology, but also in actor roles, inter-firm relationships, and the way value creation is organised.

Taken together, three closely related issues remain insufficiently understood: how incumbent infrastructure-based firms organise innovation search when established trajectories become insufficient; how external partners are identified and integrated into exploratory innovation processes; and how existing value-system

configurations enable, constrain, or are reconfigured through such exploration. These issues may also be relevant to other infrastructure-based city utilities, including water and sewage services, electricity grids, and gas networks.

Addressing these gaps requires closer empirical examination of innovation initiatives in which DH firms and their partners search beyond established technological and organisational boundaries. Such an examination can improve understanding of how radical exploration occurs in the DH sector and, more broadly, how incumbent infrastructure-based firms respond to increasing technological and market uncertainty.

1.3 Purpose and research questions

The purpose of this doctoral thesis is to understand how innovation in the district heating sector develops under conditions of energy transition. This requires examining how DH firms engage in exploration with external partners and how such exploration may reconfigure inter-firm relationships and existing value systems. The thesis addresses the following research questions:

RQ1: What characterises innovation in the DH sector under conditions of energy transition?

Addressing this question requires an understanding of how DH firms, suppliers and other partners search for and develop new solutions.

RQ2: How do district heating firms engage in exploration with external partners, and how may such exploration reconfigure existing value systems?

By addressing these questions, the thesis contributes to innovation research on incumbent firms, inter-firm collaboration, and ecosystem-based value creation, while also advancing understanding of DH as a critical urban energy infrastructure undergoing socio-technical transition.

1.4 Research settings – DH – a city utility

To support the reader's understanding of the thesis and the business logic of DH firms, this section outlines key characteristics of the heating-to-buildings domain and its institutional, technological, and organisational context. Heating to buildings constitutes a foundational societal function and a major component of final energy use, while simultaneously representing one of the most challenging domains for decarbonisation.

Historically, heating of buildings has been based on combustion of fuels such as wood, coal, coke, oil, and gas. In many countries, particularly those with extensive gas infrastructure, the dominant heating paradigm remains decentralised combustion, where households actively "set a fire" by switching on a gas boiler when heat is required and turning it off when leaving the dwelling. This paradigm is deeply embedded in both infrastructure and user behaviour. The ongoing energy transition implies a fundamental shift away from widespread combustion—except in combined heat and power (CHP)—towards electrification (heat pumps) and DH systems. Despite strong policy ambitions, the pace of this transition remains slow.

While the EU has set a target of deploying 60 million heat pumps by 2030, a substantial climate investment gap remains. At the same time, DH currently serves around 70 million people in the EU, and studies (Persson et al., 2014) indicate that available waste heat could theoretically meet a large share of total heat demand.

The scale of the challenge is illustrated by the United Kingdom, which has the highest share of individual gas-fired heating boilers in Europe. Heating accounts for approximately 80% of household energy use and around 18% of total greenhouse gas emissions[5].

In the UK, DH networks currently supply only 2% of heat demand[6], yet policy scenarios targeting Net Zero emissions envision a significant expansion, with ambitions for DH to cover up to 20% of building heat demand by 2050[7]. Investment needs for heat networks alone are estimated at £60–80 billion by mid-century[8]. New generations of DH and DC networks, including ambient and fifth-generation systems (5GDHC), further extend the potential role of network-based heating in both mitigation and adaptation[9].

In contrast to the UK, DH has achieved market shares exceeding 50% in countries such as Sweden, Denmark, and Finland, as well as significant penetration in the Baltic states and parts of Central and Eastern Europe. Nevertheless, both DH and heat pumps face challenges in replicating the long-established "instant heating" paradigm, which is characterised by rapid response and high peak supply temperatures. Replacing millennia of combustion-based heating with network-based and electrified solutions therefore represents a profound socio-technical

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5 The heat transition: Inside the race to break free from fossil fuels in buildings | Reuters

6 NAO (2024) Decarbonising Home Heating

7 CCC (2022) Independent Assessment: The UK's Heat and Buildings Strategy March 2022 and DESNZ (2024) Heat network zoning

8 DESNZ (2024) Heat network zoning: overview

9 DESNZ (2024) UK heat networks: market overview

paradigm shift, requiring not only new infrastructure but also changes in building design, customer behaviour, and system operation.

Heating provision to buildings is highly context-dependent and largely configurational in nature (Wesche et al., 2019). Unlike photovoltaic power generation or air-to-air heat pumps - technologies that have achieved generic designs with limited need for customer-specific adaptation - most heating solutions require significant engineering, tailoring, and on-site integration. DH systems, in particular, are shaped by local conditions such as building density (in the city), building load profiles, waste heat availability, legacy infrastructure, and institutional arrangements. As a result, the sector lacks dominant global players and economies of scale comparable to those found in other energy technologies. Most DH operators are municipally owned or locally anchored private firms, and few operate a dominant share of national markets.

The expansion of district heating has historically been closely linked to urban development and municipal coordination. The major build-out of DH systems in Europe occurred between the 1950s and 1980s, typically under public ownership and in synchronisation with other city utilities during large-scale urban development. Today, relatively few new DH systems are constructed, and those that are - tend to be associated with newly built urban districts. DH and district cooling are also among the youngest city utilities, particularly in comparison with water, sewage, gas, and electricity networks.

Heating markets are further shaped by regulatory frameworks and ownership models, which vary considerably across countries. In many cases, heating infrastructures exhibit characteristics of natural or legal monopolies, protected by high switching costs and technical barriers. While electricity, water, sewage, waste collection, and gas distribution are commonly regulated monopolies, DH occupies an intermediate position, with regulation ranging from strict cost-based pricing to fully deregulated markets. Denmark, for example, restricts DH operators from making profits, while Sweden allows profit-making (Salite, Miao, & Turner, 2024) and dividend payments, following deregulation in 1996 (Westin & Lagergren, 2002). Other European models include cooperative ownership, state ownership, and concession-based arrangements, such as the French model where municipalities retain ownership while outsourcing operation and maintenance. Public policy instruments, including carbon taxation - as introduced in Sweden in 1991 - have played a decisive role in shaping heating markets and accelerating the phase-out of fossil fuels, followed by new initiatives of Carbon Capture and Storage (Lindroos, Rydén, Langørgen, Pursiheimo, & Pikkarainen, 2019).

From a business perspective, DH utilities are characterised by a subscription-based logic, where customers purchase heat as a standardised commodity through long-term contractual relationships. Customer turnover is typically very low, and interactions are often arm's-length, with limited engagement beyond billing. This

business logic reinforces equal treatment, stability and predictability but also constrains incentives for experimentation and customer-oriented innovation.

DH firms operate within a broader structure of city utilities that provide essential, infrastructure-based services to buildings and industries. These include water supply, sewage and stormwater management, electricity and gas distribution, waste management, and telecommunications. City utilities are highly capital-intensive and focused on the long-term management of network assets. Many of these infrastructures face growing pressures due to ageing assets, regulatory constraints, and new demands arising from electrification, digitalisation, and climate adaptation. Bottlenecks in electricity distribution, leakage in water systems, and capacity constraints in sewage networks illustrate the systemic challenges faced by infrastructure-based utilities.

Taken together, heating to buildings represents a research setting characterised by strong path dependence, local embeddedness, regulatory complexity, and increasing pressure for radical transformation. These features make the sector particularly suitable for examining how incumbent infrastructure-based firms engage in innovation, search for new solutions, and collaborate with external actors under conditions of uncertainty.

1.5 Thesis structure

This thesis is organised in six sections, each contributing to the overall research objective.

Section 2 (Theoretical background) reviews and synthesises relevant literature on innovation, search processes, inter-firm collaboration, and value systems, ecosystem perspectives and supporting concepts. This section establishes the theoretical foundations of the thesis and develops the analytical lenses used to interpret the empirical material.

Section 3 (Research method) describes the methodological approach adopted in the thesis. It presents the research design, case selection, data collection methods, and analytical methods, as well as considerations related to research quality, rigor, and the role of the researcher.

Section 4 (Summary of appended papers) provides an overview of four papers and one book chapter that constitute the empirical core of the thesis. For each, the section summarises the research purpose, main findings, and contribution to the thesis.

Section 5 (Discussion) synthesises the findings across the individual papers. It discusses the results in relation to the theoretical framework, highlights

overarching patterns and insights, and articulates the theoretical and practical contributions of the thesis.

Section 6 (Conclusions and future research) concludes the thesis by summarising the main findings and contributions. It reflects on limitations of the study and outlines implications for practitioners, policymakers, and future research.

2. Theoretical background

This chapter develops the theoretical foundation for analysing how incumbent infrastructure-based firms innovate under conditions of path dependence and increasing uncertainty. The purpose is to establish the conceptual lenses through which innovation search, and collaboration are understood in this thesis. Path dependence relates not only to historical choices of energy distribution systems (gas, electricity, DH), but also to established technological and organisational paradigms within firms and industries.

As discussed in the preceding chapter and developed in greater detail below, moving beyond established development trajectories may require firms to shift some attention and resources from the mode of exploitation towards the mode of exploration. Exploitation focuses on refinement, efficiency improvements, and optimisation of existing technologies and routines. Exploration involves experimentation with unfamiliar knowledge, technologies and possible solutions that may subsequently result in innovation.

Innovation is understood here as more than invention (OsloManual, 2018). Following Schumpeter (2008), innovation occurs when new combinations of resources are introduced into economic life and implemented in practice (Lachmann, 1956). Innovation therefore involves the transformation of ideas into value-creating outcomes that alter products, processes, markets, organisational forms, or business models. An invention becomes an innovation only when it is applied and generates economic or societal value. In this sense, innovation implies novelty, implementation, and value creation. Schumpeter further emphasised that innovation may disrupt existing structures through processes of creative destruction (Aghion et al., 2009), where new solutions replace established ones and reshape industries over time.

The innovation process can be conceptualised as a search process, aimed at solving problems. Firms search for solutions to problems that vary in complexity and uncertainty. Some problems can be addressed through incremental improvements based on prior experience, while others require more distant, cognitive search and experimentation. The characteristics of the problem influence how search is organised and governed.

Search processes are embedded in broader value systems — the organisational structures through which value is created and delivered to customers. These configurations shape how firms collaborate, coordinate activities, and access

knowledge. Understanding shifts in search behaviour and value system configurations is therefore central to analysing radical exploration.

This chapter develops an integrated theoretical background to examine how firms move from exploitation toward exploration, how they organise innovation search, and how inter-firm collaboration influences these processes.

2.1 Incumbent firms, path dependence, the dominance of exploitation

Incumbent firms tend to innovate along established technological and organisational trajectories. This tendency is explained by path dependence (Dosi, 1982) and organisational learning theories, which emphasise how accumulated routines, skills, and investments shape future action (Nelson & Winter, 1982).

Innovation research commonly conceptualises the dynamic balance as a tension between exploitation and exploration (March, 1991) or innovation vs regulation, which also can be analysed using paradox theory (Lewis & Smith, 2022). Exploitation refers to the refinement, efficiency improvement, and optimisation of existing technologies and routines. Exploration involves search for novel alternatives that challenge existing assumptions and open up new trajectories (Levinthal & March, 1993). Few firms excel in both exploitation and exploration simultaneously, a capability referred to as organisational ambidexterity (Lavie, 2006; Lavie et al., 2010).

The literature (Xing et al., 2024) explains why in infrastructure-intensive industries such as DH, exploitation is reinforced by long asset lifetimes, high sunk costs, emphasis on operational reliability, risk minimisation, stable customer relations and low customer turnover. These conditions, to maintain status quo, favour incremental innovation, refinement, while making radical change organisationally and cognitively risky and difficult (Gavetti & Levinthal, 2000).

2.2 Radical exploration and boundary-spanning search

When incremental change and exploitation are insufficient to address emerging challenges, firms may need to engage in more exploratory forms of search. Rosenkopf and Nerkar (2001) distinguish four forms of exploration along two dimensions: organisational boundary spanning and technological boundary spanning, see figure 1. Organisational boundary spanning concerns whether search remains within the focal organisation or extends beyond it, while technological boundary spanning concerns whether search remains close to existing technologies

or moves toward technologically distant alternatives. This results in four forms of exploration. Local search remains within both the organisation and the existing technological domain. Internal boundary-spanning search remains within the organisation but explores distant technologies. External boundary-spanning search extends beyond the organisation while remaining within a relatively familiar technological domain. Radical exploration combines both dimensions: firms search beyond their organisational boundaries while simultaneously exploring technologies that are distant from their existing knowledge base (Rosenkopf & Nerkar, 2001).

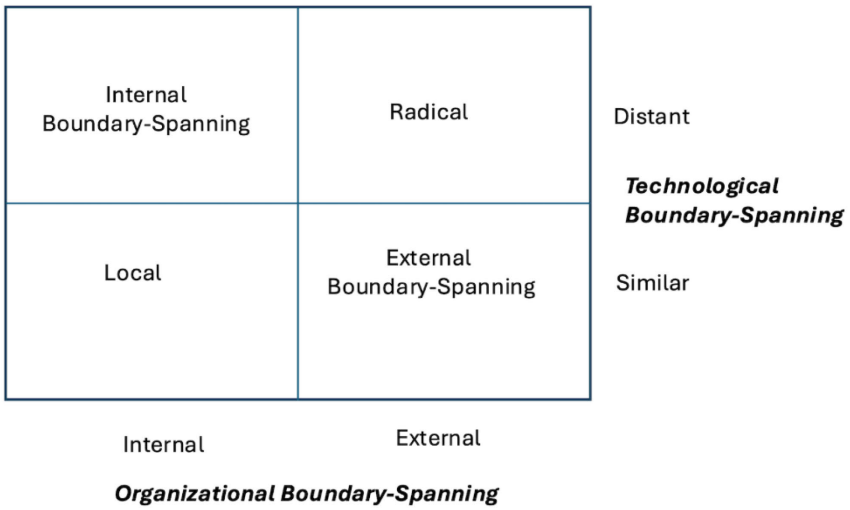

Figure 1. Four types of exploration (Rosenkopf & Nerkar, 2001).

Radical exploration therefore involves engagement with unfamiliar technologies and external actors, with considerable uncertainty regarding outcomes and performance. Feedback signals may be weak, and the return on capital may be high but delayed. Such exploration is particularly challenging for incumbents because it conflicts with established performance metrics, incentive structures, and organisational routines (Nelson & Winter, 1982). Nevertheless, under conditions of market environmental change, reliance on exploitation alone can lead to strategic inertia and innovation myopia (Gavetti & Levinthal, 2000; Levinthal & March, 1993).

2.3 Innovation search under complexity and uncertainty

Innovation search can be understood as a systematic process through which firms develop and evaluate possible solutions to problems (Gavetti & Levinthal, 2000). Problems differ in their degree of decomposability. Some can be divided into relatively independent sub-problems, whereas others are characterised by strong interdependencies that make individual choices difficult to evaluate in isolation. Baumann and Siggelkow (2013) describe search involving relatively decomposable problems as 'chunky search'.

Many contemporary challenges facing incumbents for instance DH firms - such as integrating new heat sources, adding cooling as a service, digital optimisation, or interacting more closely with customers - exhibit non-decomposable characteristics. Solving such problems requires a new type of search. Most search is experiential, based on trial-and-error learning and feedback from prior actions (Levitt & March, 1988), so-called backward-looking search. A different type of search, when there is no prior experience, is cognitive, relying on representations, models, and forward-looking evaluation of alternatives (Gavetti & Levinthal, 2000).

Incumbent firms, in stable market conditions, tend to rely on experiential, backward-looking search, which is effective in stable environments but less suited for novel and uncertain conditions (Gavetti, Helfat, & Marengo, 2017). Cognitive search allows firms to explore more distant alternatives but requires new capabilities and often external input (Gavetti & Rivkin, 2007).

Albert (2025) explains the importance of search & discovery of alternative solutions and the need to evaluate the discovered alternatives. Based on behavioural insights (Cyert & March, 1963), most search and evaluation processes are local, within a firm, reinforced by earlier experience and established routines. One explanation for the prevalence of local search is bounded rationality, which limits individuals' ability to identify and evaluate all available alternatives (Simon, 1982), demonstrated in experiments by Tversky and Kahneman (1981), where people tend to make wrong decisions, due to variation in evaluation accuracy (Knudsen & Levinthal, 2007).

Search processes can also be illustrated through fitness or solution landscapes (Kauffman, 1993). In this metaphor, different combinations of choices represent positions in a landscape, while higher points represent better-performing solutions. Highly interdependent problems create rugged landscapes with several local optima, increasing the risk that firms remain around familiar but suboptimal solutions (Ganco et al., 2020). Identifying more distant and potentially superior solutions therefore requires broader and more demanding search.

This perspective helps to explain why local exploration and search, may be insufficient for addressing system-level innovation challenges in the DH sector. A single DH firm has only access to a limited solution landscape. By engaging external partners, upstream as well as downstream, including customers, the search space expands to include more distant technologies.

When internal search reaches its limits, firms may extend their search beyond organisational boundaries. External search enables access to distant knowledge, complementary capabilities, and alternative perspectives (Cassiman & Veugelers, 2006). However, external search is not automatic. Its effectiveness depends on absorptive capacity - the ability to recognise, assimilate, and apply external knowledge (Cohen & Levinthal, 1990). Absorptive capacity is shaped by prior knowledge, learning routines, and organisational investments.

While external search expands the opportunity space for innovation, it also introduces coordination challenges, knowledge integration problems, and strategic risks related to dependency and appropriation (Rosenkopf & Nerkar, 2001).

2.4 Inter-firm collaboration and governance of innovation search

Innovation search may be organised through inter-firm collaboration when neither arm's-length market transactions nor internal hierarchy provides sufficient access to the knowledge required to address the problem. Different governance forms support different types of search (Nickerson & Zenger, 2004).

- Market-based arrangements are effective for well-defined, low-complexity problems.
- Hierarchical organisation supports coordinated problem solving but is limited by managerial attention and cognitive constraints.
- Collaborative arrangements between firms and individuals enable joint problem solving for complex, non-decomposable problems by facilitating knowledge sharing and mutual adjustment.

As discussed previously, central individuals in hierarchical organisations cannot grasp problems beyond a certain level of complexity, due to bounded rationality (Simon, 1982) and another governance is needed. For non-decomposable problems, where cognitive search is needed, a Consensus-based Hierarchy, a governance that emphasises knowledge sharing is more suitable (Nickerson & Zenger, 2004), with the firm seen as a social community (Kogut & Zander, 1992, 1996). In collaborative innovation, firms engage in repeated interaction, co-development, and joint experimentation. Such arrangements are particularly

relevant for radical exploration, where problem definitions and solution paths evolve over time.

However, collaboration also creates tensions related to control, intellectual property, and value capture, especially when partners possess overlapping or potentially substitutable capabilities (Adner & Lieberman, 2021). These three value-system configurations broadly correspond to the governance forms discussed in the preceding section.

2.5 Value systems and organisation of innovation across firms

Innovation is embedded within broader value systems that structure how activities are coordinated among firms and other organizations, and how value is created and delivered to customers across firms (Jacobides et al., 2018).

Three ideal-typical value systems are relevant:

- Market-based value systems
- Hierarchy-based value systems.
- Ecosystem-based value systems, where multiple independent actors contribute complementary offerings that must be aligned to deliver customer value.

The three types of value systems are analogous with the three types of governance forms described in the previous section.

In market-based value systems, the final customers by themselves are buying products at arms-length distance from independent suppliers. Different suppliers may have generic complementarity, but the final customers must combine and adapt products, from multiple suppliers, that work together to create the final value.

In hierarchy-based value systems, a single focal supplier controls and coordinate the activities that delivers the value to the final customer, at arms-length distance. The focal supplier has established vertical supply chains (M. Porter, 1985; M. E. Porter, 1997), with levels of suppliers, that could have competitive or cooperative ties in them between. Such value systems are effective for stable operations and incremental innovation but can constrain openness and flexibility in innovation search.

The widely used term ecosystems can be divided into three categories (Jacobides et al., 2018). The first is a business ecosystem (Moore, 1993), with loose and broadly defined relations between actors. The second is the innovation ecosystem, defined by a focal firm and independent actors´ creation of customer value, through complementary functions (Adner, 2006, 2017). The third is platform-based

ecosystems (Cusumano et al., 2019), with a platform owner and complementors adding independent value to the platform customers. A possible fourth category is industrial ecosystem (Burström, Lahti, Parida, & Wincent, 2024; Parida, Burström, Visnjic, & Wincent, 2019). Common for all the types of ecosystems is the creation of synergies between the participants, but while the first, the business ecosystem, has little connection to specific innovations, the other three types have strong relation to innovation by focal firms and complementors, interdependency and modularity between actors. Platform-based ecosystems focus on a technological or organisational platform through which complementors contribute additional value to users. Innovation ecosystems focus on a specific innovation and interconnected upstream and downstream innovations (Ganco et al., 2020). Finally, the industrial ecosystems focus on industrial processes, production systems and interconnected partners.

Ecosystem-based value systems also exhibit platform properties, which can be defined as distinctive businesses in which the more one side of the market is populated with customers, the more valuable the platform becomes to the other sides (Cusumano, 2022). To enable such network externalities, a platform typically incorporates standardised module interfaces, with modularity playing a crucial role by facilitating coordination among distinct firms to develop customer value (Jacobides et al., 2018, 2024).

Although product development platforms originated in the automotive industry (Jia et al., 2019), the concept has been widely used to describe actors in the information and communication technology sector, such as Amazon, Apple and Microsoft (Cusumano, 2022). Since platforms demonstrate ecosystem properties, platform literature emphasises the crucial role of a focal firm, or platform leader, with independent complementors strengthening the platform's customer value. With complementarity between firms comes interdependency in the creation of customer value (Ganco et al., 2020). Relations between firms can potentially change – partners who complement each other may become competitors or substitutes in the future (Adner & Lieberman, 2021).

Multi-sided platforms (MSPs) are a particular type of industry platform that enables interactions between two or more distinct types of industrial actors, where each side of the market is affiliated with the platform (Hagiu & Wright, 2015). A focal firm develops and operates the network between the actors. Based on a review of the MSP literature (Jia et al., 2019), six main characteristics of MSPs emerge. The first two characteristics stem from the foundational theory of multi-sided markets for MSPs: 1) multiple products are supplied to multiple customer categories, and 2) network effects increase the benefits for customers with additional participants on the different market sides (McIntyre, Srinivasan, Afuah, Gawer, & Kretschmer, 2021). The remaining four characteristics are: 3) The degree of openness of the platform is high. 4) Multi-homing occurs, meaning a customer can belong to more than one platform, which allows a customer to

optimise its benefits. 5) Winner-takes-all market dynamics are present, meaning that one platform may become dominant. 6) Platform envelopment occurs when one platform absorbs another platform's activities (Eisenmann, Parker, & Van Alstyne, 2011).

2.6 Integrative theoretical background

The theoretical background developed in this chapter provides an analytical framework for analysing innovation and transformation in DH firms. The framework comprises a leading concept, two explanatory mechanisms and a structural lens. In line with Blumer's work from 1954 - notion of sensitising concepts (Blumer, 2017), radical exploration is used as the leading concept of the thesis. It directs analytical attention toward how incumbent DH firms move beyond local search and incremental improvement by engaging with unfamiliar technologies and external actors.

The explanatory mechanisms (Hedström & Ylikoski, 2010) specify how radical exploration unfolds in practice. Innovation search explains how firms formulate and solve problems under uncertainty, through either experiential or cognitive search. Inter-firm collaboration explains how firms access external knowledge, complementary capabilities, and new technological options when internal search is insufficient. Together, these mechanisms connect firm-level search activities and inter-organisational relationships with evolving innovation outcomes.

The structural lens (Cornelissen & Durand, 2014) is provided by the literature on value systems, ecosystems, and platforms. This lens makes it possible to analyse how innovation changes not only technologies and firm behaviour, but also actor roles, interfaces, governance arrangements, and the coordination of value creation across firms.

Accordingly, radical exploration constitutes the leading concept; innovation search and inter-firm collaboration provide the explanatory mechanisms; and value systems, ecosystems and platforms offer a structural lens for interpreting how innovation is organised across actors.

3. Research method

This chapter outlines the methodological approach used to address the overall purpose and research questions of the thesis, as well as the specific objectives of the appended papers. It explains the research context, overall strategy and design, data collection and sampling procedures, analytical techniques, the role of the researcher, and measures taken to ensure research quality and transparency. Particular attention is given to the benefits and potential biases associated with my insider position and to the measures taken to address these methodological challenges. The methodological choices are guided by the exploratory nature of the research problem and by the need to capture complex innovation processes unfolding over time and across organisational boundaries.

3.1 Research context, access and my role as researcher

I have more than three decades of international professional experience in management positions, primarily in companies supplying products and consultancy services to the energy sector. During this period, I encountered recurring questions and tensions for which existing industry explanations appeared insufficient. Examples of these questions and tensions are presented in the introduction to this thesis.

The empirical work of this thesis is embedded in the context of European district heating (DH) systems undergoing transformation as part of the broader energy transition. Over the course of the research period, I was engaged in several national and European research and innovation initiatives, including EU Horizon projects (e.g., REWARDHeat), Swedish innovation programmes funded by Vinnova (e.g., TermoNet, SAM Smart Asset Management), and the export–collaboration platform ‘Sustainable Heating and Cooling by Sweden’ (including SweHeat and Cooling - Swedish Council for DH, Swedish Energy Agency and Business Sweden). Participation in these initiatives provided extensive access to DH projects and actors engaged in the development and implementation of new technologies and organisational arrangements. This access facilitated longitudinal observation, case identification, respondent recruitment, and iterative validation of empirical interpretations. Such embeddedness is particularly valuable when studying emerging and uncertain phenomena, where formal documentation is limited and much relevant knowledge resides in ongoing practices and interactions.

My insider–outsider position enabled informed interpretation of technical and organisational practices while also requiring reflexivity regarding potential biases. Prolonged engagement, transparency in data collection, and continuous peer and expert feedback were used to mitigate such risks. Table 1 summarises my contribution to the five appended papers.

Table 1. My contribution in the five appended papers

Paper	Status	Paper Title	My contribution
Paper I	Published	Is Innovation Redesigning District Heating? A Systematic Literature Review	Conceptualising the research idea and objective, formulating the review and search protocol, database search and coding, writing the literature review and method sections, analysing the data, and preparation of both the original and revised manuscripts for journal submission.
Paper II	Published	Opportunities for Machine Learning (ML) in District Heating	Conceptualising the research idea, collecting and coding data from observations, writing findings and discussion, reviewing original and revised manuscript.
Paper III	Submitted	Shifting between complementor and supplier relations in digital product-service system innovations	Idea generation, pilot investigation, conceptualisation of the research idea, searching literature, formulating the research questions and objective, designing the study, selecting cases, sampling of respondents, collecting data, interviews, analysing data, writing finding and discussion, preparing submission - original and revised manuscript.
Paper IV	Published	From islands to platforms: Innovation pathways for district heating firms across Europe	Idea generation, pilot investigation, conceptualisation of the research idea, searching literature, formulating the research questions and objective, designing the study, selecting cases, sampling of respondents, collecting data, interviews, analysing data, writing finding and discussion, preparing submission - original and revised manuscript.
Paper V	Published	Ecosystems, capital structure, and entrepreneurial action	Collecting empirical data on ecosystems, theoretical conceptualisation, reviewing original and revised manuscript

3.2 Research strategy and design

The research questions are primarily exploratory and concern how innovation search and external collaboration develop under conditions of uncertainty. Addressing these questions requires in-depth investigation of organisational practices, relationships, and innovation processes, particularly in the empirical studies in Papers III and IV, which are difficult to capture through purely quantitative methods (Bell, Bryman, & Harley, 2022; Creswell & Creswell, 2017).

The thesis follows a predominantly qualitative research strategy, with methods selected according to their suitability for addressing the research questions. This pragmatic orientation allows different but complementary research designs to be

combined across the five papers, while maintaining an emphasis on transparency, empirical grounding and methodological coherence (Creswell & Creswell, 2017).

Within qualitative research, the case study design is particularly suitable for examining contemporary phenomena in their real-life context, especially when the boundaries between phenomenon and context are blurred (Goffin, Åhlström, Bianchi, & Richtnér, 2019; Yin, 2017). Innovation search and inter-firm collaboration are deeply embedded in organisational routines, governance structures, and institutional environments. A case study approach enables the researcher to capture these contextual conditions and explore complex causal processes over time (Eisenhardt, 1989). Case studies are especially appropriate for theory development in areas where existing explanations are incomplete or fragmented. Respondents from 22 organisations were interviewed, and the resulting material was analysed as part of the individual studies, as summarised in Table 2. More than 20 additional organisations contributed contextual insights through workshops, observations and less formal interactions, although these were not subjected to the same systematic analysis as the primary cases. The selected firms are DH operators or suppliers to DH firms, or municipal employees. Firms and respondents were purposively selected to provide information-rich empirical material. The thesis comprises five interrelated papers employing complementary research designs, as summarised in Table 2:

- **Paper I**: A structured literature review (SLR) combining qualitative synthesis with descriptive quantitative elements.
- **Paper II**: An exploratory position paper drawing on qualitative material from open-ended survey questions, workshops, interviews, observations and a literature review.
- **Paper III**: An embedded, longitudinal single-case study aimed at theory building on innovation search and inter-firm relations.
- **Paper IV**: A comparative multiple-case study across several European contexts.
- **Paper V**: A conceptual, theory-developing study that builds primarily on empirical insights generated in Papers III and IV.

The empirical case studies in Papers III and IV were originally designed around focal firms and the innovation processes in which they participated. At the level of the individual papers, the focal firm therefore constitutes the main case entry point. However, the cross-paper synthesis in this thesis compares innovation initiatives rather than firms as such. An innovation initiative refers to a distinct process through which a focal actor searches for and develops a new technological, organisational, or service-related solution.

Participating firms and their relationships are examined as embedded elements within these initiatives. This distinction is important because the same organisation may participate in several innovation initiatives that differ in technological novelty, search behaviour, actor involvement, and governance. At the thesis level, the principal analytical focus is therefore inter-organisational: how actors search, collaborate, coordinate activities, and potentially reconfigure existing value-system arrangements. Sectoral and institutional conditions are treated as contextual factors that help explain differences between initiatives.

Together, the five papers address different parts of the overall research problem. Paper I maps innovation research in the DH field, Paper II examines emerging technological opportunities, Papers III and IV provide the main empirical analysis of innovation search and inter-firm relationships, and Paper V develops a conceptual synthesis. The papers therefore operate at partly different analytical levels, but the thesis-level synthesis is centred on innovation initiatives and the inter-organisational relationships through which they develop. This logic connects the individual papers to the overall research purpose and explains how the thesis moves from mapping and empirical exploration toward conceptual synthesis.

The papers draw on complementary sources of evidence, including literature reviews, interviews, workshops, observations, and documentary material. Their respective roles and data-collection procedures are described in Section 3.3 and summarised in Table 2. Together, these sources support the cumulative analysis of innovation search and transformation across the five papers. Figure 2 summarises the overall research design and its relationship to the research questions, while Table 2 presents the methods applied in the individual papers.

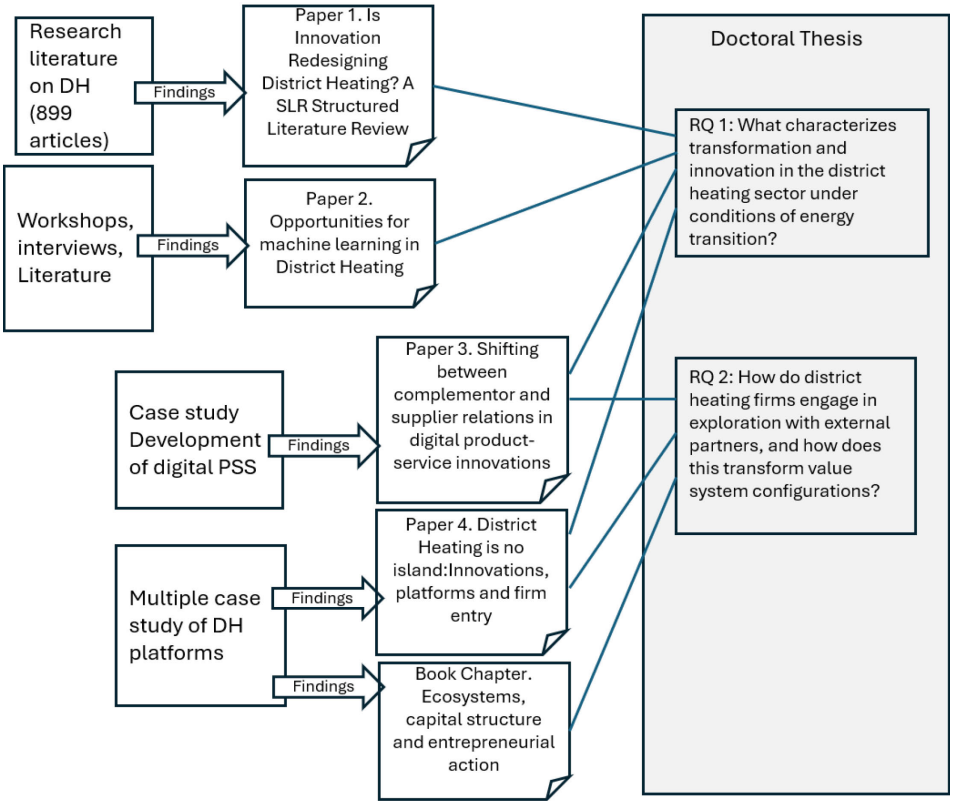

Figure 2. Research design with literature review, interviews and cases, resulting in five papers and the contribution to the thesis research questions (RQs).

Table 2 summarises the primary empirical focus, cases/samples, data collection, and triangulation for each paper. At the thesis level, innovation initiatives constitute the units of comparison in the cross-paper synthesis, with participating firms and relationships examined as embedded elements.

Table 2. Papers, research questions, empirical focus, cases, sampling, data collection and triangulation.

Paper	Research questions	Primary empirical focus	Case/ Sample	Data Collection	Triangulation of data
Paper I	What characterises innovation in the DH sector?	DH research field	SLR, 899 Papers	2 scientific databases, Scopus and Ei Compendex	Expert feedback
Paper II	What is the status of AI/ML, possibilities and challenges from the perspective of DH industry and research?	DH industry and research community	98 respondents in total and 92 articles	4 workshops to create domain insights, 2 open question surveys with interviews and a literature review.	Expert feedback
Paper III	How does a service-oriented firm search for and engage external partners during the development of a digital product-service system? Why and when does the firm shift between complementor and supplier relations during this innovation process?	Focal firm and inter-firm innovation process	(Embedded) single case with 27 respondents from 14 firms	13 retrospective open interviews. 29 semi-structured interviews 74 observations in meetings and workshops, 14 site visits	Expert feedback presentations Internal protocols Business plans User manuals, Handbook
Paper IV	How DH firms innovate to create and deliver new value by changing their technological and inter-firm engagements, as well as their organisational boundaries?	Focal firm and inter-organisational innovation configuration	7 cases, with 7 firms and other actors around them	39 observations in meetings, presentations and workshops. 56 semi-structured interviews.	Expert feedback, Internal documents, project reports, scientific papers, presentations
Paper V	How do entrepreneurial actions transform ecosystems following the introduction of a new capital resource?	Conceptual / value-system and ecosystem level	Conceptual study		Discussions among the authors

3.3 Data sampling and collection

While Section 3.2 has outlined the overall qualitative research strategy and case study design, the following section details how this design was implemented in practice. Section 3.3 describes the procedures for data sampling and collection, including case selection, actor identification, and data sources across the included papers. Clarifying these steps strengthens the transparency and methodological rigor of the study.

Sampling procedures differed between the individual studies. In the empirical case studies, access to potential cases was partly facilitated by my involvement in industry and research networks. From these accessible settings, cases were purposively selected based on their relevance to the research questions and the innovation processes under investigation. Within cases, respondents were selected based on their involvement in innovation processes, strategic decision-making, or

technical development. Snowball sampling was used to identify additional informants with relevant or complementary perspectives.

Across the five papers, data sources include semi-structured interviews, participant and non-participant observations, workshops, surveys, internal documents, project reports, and scientific and industry publications. This multi-source approach enabled triangulation and enhanced the robustness of empirical insights.

3.3.1 Structured Literature Review (SLR)

Paper I employed a SLR to map and analyse innovation-related research in district heating. Searches were conducted in Scopus and Ei Compendex due to their comprehensive coverage of peer-reviewed engineering and management research. Search strings were developed iteratively through pilot searches and refined to balance breadth and relevance. Multiple searches were combined, and duplicates were removed.

The final dataset comprised 899 publications, which were systematically coded according to innovation phase, level of analysis, and position in the DH value chain, see details in table 2. Keyword frequency analysis was used to identify dominant themes and research gaps. This review provided both a foundation for the thesis and a benchmark against which empirical findings could be interpreted.

Analysing existing literature is crucial in any research journey, as it is the foundation for understanding and advancing a field (Bell et al., 2022). By using a SLR method, I was able to categorise research, avoiding duplication of my own research and finding knowledge gaps.

3.3.2 A road map for machine learning and district heating

Paper II examined the development and application of artificial intelligence and machine learning in DH through a qualitative position paper design. Data were collected through open question surveys targeting industry and academic experts, observations and notes from expert workshops, and a focused state-of-the-art literature review. The combination of empirical expert input and literature analysis enabled identification of mismatches between industrial challenges and prevailing research trajectories, see details in table 2.

3.3.3 Case studies

Case study methodology was central to **Papers III and IV**. Case studies are well suited to investigating contemporary phenomena in real-life contexts (Goffin et al.,

2019), particularly for "how" questions where the boundaries between the phenomenon and its context are blurred (Yin, 2017) and where organisational relations are central. The approach aims to provide deep and wide understanding, by producing a detailed description and analysis of a single case or multiple cases (Bell et al., 2022). Case studies can employ an embedded design that is multiple levels of analysis within a single case study (Yin, 2017).

Paper III is based on a longitudinal, embedded single-case study of a technology supplier engaged in a decade-long transition from manual services to digital, product–service solutions, involving multiple external actors in various roles. Data were collected through semi-structured interviews with 27 informants across 14 organisations, complemented by observations, site visits, and internal documentation, see details in table 2. Some respondents were interviewed several times. Snowball sampling led to additional interviews and observation after the first round of interviews (Biernacki & Waldorf, 1981) until the authors felt that a point of saturation was reached. The four-year longitudinal design enabled detailed reconstruction of the innovation search process and evolving inter-firm relations (Beverland & Lindgreen, 2010). Informants were asked about the development process and were encouraged to discuss their main concerns (Drever, 1995).

Paper IV employed a multiple-case study design involving DH firms in Sweden, France, and the Netherlands, see details in table 2. Cases were selected based on three criteria: 1) DH as core business, 2) emphasis on sustainable heat supply, and 3) provision of additional customer value, particularly through cooling services. Data were collected between 2019 and 2024 through interviews, workshops, observations, expert feedback, and secondary sources. The comparative design enabled identification of patterns and variations across institutional and technological contexts.

Access to potential cases was facilitated by the main author's proximity to actors and phenomena through industry and research networks (Yin, 2009). From this accessible pool, cases were purposively selected using the three criteria described above. The selection process involved two steps. First, fifteen potential cases meeting the selection criteria were identified through public sources, research papers, web material, articles, and expert interviews. Second, seven cases were selected to provide variation in incumbency, institutional context, and firm size. Additional cases were not included once they were judged to provide limited additional variation or analytical insight (Dubois & Gadde, 2002, 2014).

Data were collected using a combination of qualitative data collection methods to triangulate responses and mitigate potential biases (Dubois & Gadde, 2002; Gailing & Naumann, 2018; Goodman & Marshall, 2018). As shown in Table 2, these methods included 1) semi-structured interviews and follow-up interviews lasting between 30 and 60 minutes with firm informants and industry experts, city planners, and suppliers; 2) participatory observation in several industry-relevant

project meetings such as TermoNet funded by Sweden's innovation agency Vinnova and REWARDHeat funded within EU Horizon 2020; 3) feedback from independent experts; and 4) secondary data collection in the form of scientific papers, reports, internal documents, and web content. This diverse set of data allowed for triangulation across multiple sources, increasing the validity of observed patterns. In total, we conducted 56 interviews (approximately 40 hrs in total) and attended 39 meetings with external actors, 35 as observers and four as workshop organisers.

Paper V is a conceptual, theory-developing paper informed by empirical insights into emerging ecosystems generated in Papers III and IV.

3.3.4 Innovation initiatives and participating actors

This section introduces the innovation initiatives and participating actors drawn from the empirical material in Papers III and IV. While the individual case descriptions are presented in the respective papers, a consolidated overview of the selected innovation initiatives is provided here to support the cross-case discussion in Section 5, see figure 4. The purpose of presenting these initiatives jointly is analytical rather than descriptive: they constitute the empirical basis for examining patterns of innovation search, inter-firm collaboration, and shifts in value system configurations.

From the broader empirical material reported in Papers III and IV, ten innovation initiatives were selected for the cross-paper synthesis. The initiatives involve different focal actors, including DH firms, property owners, and technology suppliers. Some organisations appear in more than one initiative because they participated in distinct innovation processes with different technological, organisational, and relational characteristics.

This illustrates why the innovation initiative, rather than the firm itself, is used as the unit of comparison in the cross-paper synthesis: the same organisation may engage in different forms of search and collaboration depending on the problem addressed, the technology involved, and the participating actors.

The focal actors are anonymised to ensure confidentiality. They vary in terms of technological focus, degree of collaboration, and proximity between internal and external search. In the discussion chapter, these actors are positioned analytically according to their innovation characteristics and relational configurations, enabling comparison across cases.

The following descriptions provide sufficient contextual information to understand each initiative's role in the empirical analysis.

Initiative 1: A DH firm from Sweden that has implemented a digital Product Service System for pipeline surveillance.

Initiative 2: A DH firm from Sweden that has implemented a digital Product Service System for customer integration.

Initiative 3: A DH firm in Sweden that has installed a heat-driven cooling solution in the customer building.

Initiative 4: A DH firm in Sweden that has developed a cooling service for an individual large customer. The waste heat that is collected in the cooling process is upgraded and distributed to DH customers.

Initiative 5: An energy service company, a DH firm in Sweden, that has implemented a combined solution for heating and cooling (5GDHC) to a large property owner and additional neighbour property owners.

Initiative 6: A DH firm in the Netherlands that has developed a new combined DH and cooling service solution (5GDHC).

Initiative 7: A DH firm in France that is operating a DH system (5GDHC) based on waste heat from a cooling process to a large property owner.

Initiative 8: A property owner in Sweden that is providing energy services, heating and cooling to a group of multifamily buildings, offices, school and hotel.

Initiative 9: A property owner in Sweden that is operating their own energy service company, providing heating and cooling to hotel, offices, school and housing associations in a city district.

Initiative 10: A product supplier of a new solution to repair DH pipes.

3.4 Data analysis

Data analysis followed established qualitative procedures and was adapted to the purpose and design of each paper. The analysis involved both empirical interpretation and iterative theory development.

Phenomenon-based theorising starts from an empirically important or under-theorised phenomenon and seeks to understand it by relating observations to existing theoretical explanations (Fisher, Mayer, & Morris, 2021). Rather than proceeding exclusively through deduction or induction, it allows empirical observations and theoretical concepts to inform one another iteratively. Deductive theorising begins primarily from existing theory and examines its implications for specific empirical instances, whereas inductive theorising develops more general concepts and explanations from observed empirical patterns. This type of theorising differs from purely deductive and inductive approaches (Fisher et al.,

2021). Deductive theorising begins from existing theory and moves from general propositions toward specific empirical instances through logical reasoning. Inductive theorising proceeds from specific empirical observations toward more general concepts and explanations by identifying patterns in the data.

Phenomenon-based theorising shares similarities with abductive theorising, particularly in its focus on unexplained anomalies, contradictions, or surprising observations that require theoretical explanation (Sætre & Van de Ven, 2021). While abductive theorising generates and evaluates possible explanations that make such anomalies more understandable (Fisher et al., 2021), phenomenon-based theorising starts from an under-theorised empirical phenomenon and connects it to existing theory in ways that may also extend or refine that theory. This approach encourages researchers to remain attentive to emerging phenomena through observation, experience, dialogue, data complications, and illustrative examples, rather than relying solely on conventional coding of empirical material. Van de Ven (2016), citing Schwarz and Stensaker (2015), stresses the importance of grounding the phenomenon in practice, defining phenomenon-driven research as "problem-oriented research that focuses on capturing, documenting, and conceptualising organisational and managerial phenomena of interest in order to facilitate knowledge creation and advancement." However, this approach also involves risks. Researchers may produce biased interpretations when addressing complex phenomena, and the research problem may remain insufficiently grounded if it is not developed in close engagement with those who experience and understand the phenomenon in practice.

These approaches to theorising can complement one another, and phenomenon-based theorising can be useful when it is uncertain whether one or several theoretical explanations may account for a phenomenon. Phenomenon-based theorising is used here not as a separate overarching research methodology, but as a way of describing how empirical observations of under-theorised developments were iteratively related to existing theory.

In the empirical case studies, the analysis proceeded across several related levels. First, each innovation initiative was reconstructed by identifying the problem addressed, the technologies involved, the sequence of development activities, and important changes over time. Second, the participating actors and their relationships were analysed, including their roles, knowledge contributions, dependencies, and division of responsibilities. Third, the initiatives were compared at an inter-organisational level, focusing on how collaboration affected organisational boundaries, governance arrangements, and the configuration of value creation. These relational configurations were subsequently interpreted through the theoretical lenses of hierarchy-based, market-based, and ecosystem-based value systems. Finally, sectoral and institutional conditions, including ownership, regulation, market conditions, and legacy infrastructure, were considered when explaining differences between the initiatives.

In **Paper I**, publications were coded into mutually exclusive categories and analysed using keyword clustering as a proxy for thematic emphasis. Innovation phases and levels of analysis were used to distinguish between exploratory insights and more development-oriented contributions. An initial coding was applied to identify publications related to technological, business, or social aspects of innovation within the dataset generated by the five database searches. Given the broad scope of technologically oriented publications, these were further sorted into six categories following the conventional DH value chain (Frederiksen & Werner, 2013). All relevant articles were coded to one group only, and all groups were made mutually exclusive. Each group was analysed according to keyword frequency. The keywords were used as a proxy to identify clusters (themes of similar keywords). Approximately 100 keywords were analysed per group. Papers from two groups, distribution and heat transfer, were scrutinised further as these activities are at the core of DH activity and, as a result of the many decades of DH operation, were expected to contain evidence of innovation activity. The papers in the two groups were coded in terms of different stages of innovation 'phase' and unit of analysis (component, product or service) referred to as 'level'.

Paper II combined thematic analysis of interview data, workshop observations, and responses to open-ended survey questions with comparative analysis of relevant literature streams. Three methods for data analysis were applied. First, brainstorming was conducted in workshops to develop a better understanding of the problem area. Brainstorming is commonly used during the idea-generation phase of scientific inquiry (Isaksen, 1998). A series of workshops and discussions involving experts from different R&D projects and the DH industry were observed, documented, and coded. The interdisciplinary nature of the workshop participants with different competences revealed differing expectations related to data analytics and DH. Second, an inventory of existing knowledge was made. Problem areas identified in step 1 were further expanded through a review of relevant literature in the area, but also through consultative discussions with DH experts. Industry publications were also analysed to identify problem areas in DH. To understand how ML research has developed in the area of DH, a state-of-the-art literature review (Grant & Booth, 2009) was completed, using specific phrases, with the help of Harzing's Publish or Perish software (Harzing, 2010). Third, existing knowledge was analysed to determine the extent to which DH-relevant problems had been addressed in ML research. Other literature reviews were analysed to determine whether they provided enough of an overview of how ML has been applied in the field of DH.

In **Paper III**, analysis proceeded through iterative cycles of inductive and deductive reasoning. First, detailed case histories were constructed. We started with a thematic data analysis (Corbin & Strauss, 1990) to categorise the interviews and the supporting data. We created a chronological case history, which revealed information about how the focal firm searched for innovation over approximately

ten years, and summarised important events in the search process of the focal company. We combined interviews and observations to triangulate information on the specific events to establish their correct chronological sequence. Second, open coding was applied to identify first-order concepts. These were subsequently grouped into second-order categories informed by theoretical constructs such as search modes, inter-firm relations, and value system configurations. We focused on identifying patterns in the innovation search process by moving between inductive and deductive reasoning (Hoffman & Ocasio, 2001; Walsh & Bartunek, 2011) to create a list of first-order codes from the evidence in our case history, see Corbin and Strauss (1990) and Gioia, Corley, and Hamilton (2013). We then applied deductive reasoning using theoretical concepts and searched for frameworks that might help to explain the emerging data coding. We grouped the first-order codes according to key business occurrences. Finally, the codes were organised into mechanisms reflecting the type of technological search (similar, distant) (Rosenkopf & Nerkar, 2001), search heuristics (cognitive or experiential) (Gavetti & Levinthal, 2000) and inter-firm relationship (complementor or supplier). This resulted in four different aggregate dimensions. We organised the theoretical categories into third-order aggregate dimensions related to the mode of inter-firm relation.

In **Paper IV**, data were collected in Swedish and English. Interviews, workshops, and observations were documented through field notes (Bell et al., 2022). The notes captured essential information and key ideas while excluding details not relevant to the research purpose. In line with Emerson, Fretz, and Shaw (2011), this approach supported responsive and embedded engagement with informants and research settings, facilitating a deeper insider approach to data collection. Extracts used in the study were translated and, where necessary, paraphrased by the authors.

Comprehensive case histories were written to provide an overview of the cases and their characteristics. We applied systematic combining to refine existing theory and empirical understanding rather than to create or test theory (Dubois & Gadde, 2014). This involved continuously matching the theoretical framework, data sources, and analysis through iterative movement between empirical observations and theoretical interpretation. Informed by this approach, we manually coded the data and conducted the analysis by focusing on finding patterns within and between cases. This process was also guided by initial ideas on case-comparison patterns generated during the write-up of each case. The platform and later the disruption literatures were brought to explain the changes in interorganisational relations and patterns of innovation following entry of new DH actors. Continuous triangulation with industry experts and peer debriefing among the authors played a critical role in advancing the analysis.

At the thesis level, findings from Papers III and IV were compared across innovation initiatives rather than solely across focal firms. The comparison focused

on technological distance, the organisational location of search, the actors involved, the form of collaboration, and the extent to which existing arrangements for value creation were altered. This cross-case comparison supported the identification of the five patterns presented in Section 5.2. The patterns are treated as analytical ideal types rather than as fixed categories of firms or sequential stages of transformation.

Paper V synthesised empirical insights from Papers III and IV with theory to develop conceptual arguments about ecosystems and entrepreneurial action.

3.5 Research quality

A major challenge in qualitative research is to assess and demonstrate that a study is rigorous, accurate, and relevant (Schwandt, Lincoln, & Guba, 2007). To strengthen this thesis and its papers, several measures were implemented throughout idea generation, pilot studies, data collection, analysis, and writing. As explained in the previous sections, these measures included extensive triangulation of data. Informants provided consent before interviews and observations. Preliminary findings were presented to co-authors and industry experts and discussed at workshops and conferences. Finally, the papers were submitted to journals for peer review, providing external scrutiny and opportunities for improvement.The Case Study Evaluation Template (CASET) provides a structured framework for assessing the methodological quality of case studies in innovation management (Goffin et al., 2019). It was applied to assess the case-study components of this thesis, particularly Papers III and IV, against ten criteria of methodological rigour, as summarised in Table 3.

In line with ethical guidelines and good research practice (Lin, 2023), I acknowledge the use of ChatGPT® for grammar and spelling support of this thesis (kappa). All analytical judgments, interpretations, and conclusions remain my sole responsibility.

Table 3. Evaluation of the case-study research in Papers III and IV based on the CASET template (Goffin et al., 2019).

	Evaluation Criteria	Assessment of paper III and IV
Research Design	**Theoretical foundation**: Was a clear explanation given why the case method was the most appropriate to adopt?	Fulfilled. Case study method was employed to provide rich descriptions. The approach allowed for in-depth exploration of contextual factors that are important to understand the firms analysed in Papers III and IV.
	Pilot Study: Was there a pilot study preceding the main study?	Fulfilled. Pilot studies, exploratory interviews and analysis were conducted. A semi-structured interview approach was applied, where questions were adapted to the response, in multiple iterations of interviews.
	Theoretical sampling: Was an explanation provided of which cases were chosen and why?	Fulfilled. The rationale for selecting cases in Papers III and IV is explicitly described. Cases were purposively selected based on their relevance to the research questions and the innovation processes under investigation.
Data Collection	**Triangulation**: Was the research based on multiple sources of data?	Fulfilled. Papers III and IV combined multiple data sources, including interviews, observations, workshops, documentary material, and expert feedback, enabling triangulation across sources.
	Review and validation of evidence: Was the evidence reviewed and validated by external parties?	Fulfilled. Findings from the papers were presented, discussed and validated by several external experts from industry and from academia.
	Transparency of data collection: Was it made clear how data collection process was conducted?	Fulfilled. The process for data collection, from interviews, observations and other secondary data were thoroughly explained in the method sections of Paper III and IV. Data was presented in structures and tables, offering a clear view of how data were collected and analysed.
	Inter-coder agreement: Were the data coded by multiple investigators?	Fulfilled. Data were coded primarily by me, as the main author, and the coding and interpretations were reviewed and discussed with the co-authors.
Data Analysis	**Case presentation**: Were findings and empirical evidence presented in a way that made it clear how the authors reached their conclusions?	Fulfilled. In order to make the connection between data and conclusions more transparent, data structures and direct quotes were presented in Papers III and IV, facilitating a clearer discussion of the findings.
	Case interpretation: Did the case analysis move beyond description and conceptual ordering?	Fulfilled. Through abstraction, explanation, and conceptual synthesis, the analysis moved beyond description and contributed to the development of frameworks and models.
Post-hoc	**Reflecting on validity and reliability**: Was there a discussion about the quality of the research?	Fulfilled. Both studies discussed their methodological choices and underwent informal and formal peer review through journals, conferences, and workshops. This reflective practice strengthened the rigour of the studies.

4. Summary of appended papers

This section presents the five papers that constitute the empirical and conceptual foundation of the thesis. Together, the papers address the overall research purpose and research questions by examining innovation search, external collaboration, and value system configurations in the context of district heating and heating to buildings.

The papers are complementary and cumulative, with their overall logic lying in how they move across analytical levels: from the research field and technological opportunity space to firm-level innovation search, inter-firm collaboration, value-system change, and finally ecosystem transformation.

Each paper focuses on a specific aspect of the research problem, employs an appropriate methodological approach, and contributes distinct insights. Taken together, they triangulate across methods, levels of analysis, and empirical contexts, while also supporting theory development through comparison and synthesis.

The papers progress from a broad mapping of existing research to in-depth empirical analysis and conceptual development. The structured literature review provides an overview of how innovation in DH has been studied and identifies key gaps that motivate the empirical work. Subsequent papers draw on qualitative and longitudinal data to analyse innovation search processes, inter-firm relationships, and collaborative arrangements in incumbent DH firms. The final paper synthesises empirical insights to develop conceptual arguments relevant to innovation and ecosystem research.

Three papers have been published in peer-reviewed journals, one has been published as a peer-reviewed book chapter, and Paper III has been submitted to a peer-reviewed journal. The author's contribution to each paper is described, in previous section, table 1.

Table 4 summarises the papers, RQs, key findings and RQ addressed. The research method applied in each specific paper is presented in section 3.

Table 4. Summary of the appended papers´ research questions and key findings.

Paper	Research Question	Key findings	Thesis RQ addressed
Paper I	What characterises innovation in the DH sector?	The systematic literature review shows that DH research is dominated by system-level, production-oriented, and environmental-impact perspectives, while relatively little research explicitly addresses innovation, management challenges, customer relations, or inter-organisational collaboration. This highlights the limited attention given to firm-level innovation and external relations in the DH literature.	RQ1
Paper II	What is the status of AI/ML, possibilities and challenges from the perspective of DH industry and research?	Digitalisation, IoT, cloud computing, AI and ML offer substantial opportunities for improving planning, monitoring, optimisation and control in DH. However, the study identified a mismatch between dominant ML research and broader industry challenges, highlighting both technical and non-technical barriers and the need for greater cross-disciplinary and cross-organisational collaboration.	RQ1; support RQ2
Paper III	How does a service-oriented firm search for and engage external partners during the development of a digital product-service system, and why and when does it shift between complementor and supplier relations?	Complementor and supplier relations evolve during digital PSS innovation. Complementors enable access to complementary technologies and low-cost experimentation under uncertainty, while increasing technological interdependencies, lock-in and control problems may trigger a shift toward supplier relations. Later complementor search may support further value expansion but can also create role ambiguity and competitor risk.	RQ2; support RQ1
Paper IV	How DH firms innovate to create and deliver new value by changing their technological and inter-firm engagements, as well as their organisational boundaries?	The study identifies three pathways through which DH systems move beyond traditional hierarchy-based configurations: incremental improvement by incumbents, collaborative entry through new platforms complementing incumbent DH infrastructure, and disruptive entry through independent heating and cooling platforms. Across the pathways, innovation increasingly depends on new inter-firm configurations integrating DH, heat pumps, cooling, storage and customer-side resources.	RQ1, RQ2
Paper V	How do entrepreneurial actions transform ecosystems following the introduction of a new capital resource?	Building on ecosystem theory and Austrian capital theory, the paper shows how entrepreneurial action following the introduction of a new capital resource may reinforce an ecosystem or transform it toward a hierarchy-based or market-based value system. The likelihood and direction of transformation depend on knowledge abstraction, multiple specificity and accessibility of the new capital resource.	Support RQ2

4.1 Is Innovation Redesigning District Heating? A Systematic Literature Review

The paper was published in 2021 in Designs (https://doi.org/10.3390/designs5010007). (This article belongs to the Special Issue **Planning for Home Renewable Energy Systems**)

Authors: Håkan Knutsson, Magnus Holmén, Kristina Lygnerud.

Purpose. The purpose of the paper was to better understand innovation in the DH sector and its characteristics.

Findings. The systematic literature review analysed 899 articles and classified the DH research field into eight main areas: fuel, supply, distribution, transfer, DH system, city system, impact, and business. Most publications were concentrated in supply, DH systems, and environmental impact, showing that the field has been dominated by system-level and production-oriented perspectives. In contrast, relatively little research addressed firm-level innovation, management challenges, asset management, customer relations, or inter-organisational collaboration. Only a limited number of studies explicitly applied innovation theory, suggesting that innovation in DH has often been treated indirectly as technological development, system improvement, or environmental performance rather than as an organisational and strategic process. The review therefore indicates that the sector has largely developed through incremental improvements within established technological and organisational structures, with comparatively limited attention to external relations, customer-oriented innovation, and the mechanisms through which more substantial transformation occurs.

Contribution to the thesis. Paper I contributes to the thesis by establishing the empirical and conceptual foundation for the research problem. The systematic literature review shows that DH research is dominated by system-level, production-oriented, and environmental-impact perspectives, while firm-level innovation, management challenges, asset management, customer relations, and inter-organisational collaboration remain underexplored. This motivates the thesis focus on how DH firms search for innovation and collaborate with external actors under conditions of energy transition.

The paper contributes mainly to RQ1 by showing that innovation in the DH sector is uneven, incremental, and strongly shaped by established technological and organisational trajectories. It also contributes indirectly to RQ2 by identifying a lack of research on external relations, customer interaction, and collaborative innovation. In this way, Paper I provides the starting point for the later papers, which move from a broad mapping of the DH literature toward detailed analysis of digitalisation, radical exploration, inter-firm collaboration, platform-based innovation pathways, and ecosystem transformation.

4.2 Opportunities for Machine Learning (ML) in District Heating

The paper was published in 2021 in Applied Sciences
(https://doi.org/10.3390/app11136112)
(This article belongs to the Special Issue **Advances in Artificial Intelligence: Machine Learning, Data Mining and Data Sciences**)

Authors. Gideon Mbiydzenyuy, Sławomir Nowaczyk, Håkan Knutsson, Dirk Vanhoudt, Jens Brage, Ece Calikus.

Purpose. The purpose of this article was to chart and discuss to what extent state-of-the-art ML has addressed key challenges in the DH industry, to identify discrepancies between the two fields and to propose a roadmap with suitable goals for how to increase the impact of ML in DH.

Findings. Digitalisation, increasingly affordable IoT solutions, and cloud-based computing create substantial opportunities for applying AI and Machine Learning (ML) in DH. Potential applications include planning, monitoring, forecasting, optimisation, control, predictive maintenance, fault detection, and demand-side management. However, the study identified a mismatch between the dominant directions in ML research, particularly forecasting, and the broader operational and organisational challenges faced by DH firms. A roadmap was therefore proposed, ranging from open-source benchmark datasets to improved access to data and methods for empowering consumers. The findings show that realising the potential of ML requires overcoming both technical and non-technical barriers, including data availability, integration of different knowledge domains, and collaboration between DH firms, technology suppliers, researchers, software actors, and customers. Overall, the paper demonstrates considerable potential for AI and digitalisation to contribute to DH transformation, while also showing that innovation progress is relatively slow and that cross-sector and cross-organisational collaboration remains underdeveloped.

Contribution to the thesis. Paper II contributes to the thesis by positioning machine learning and digitalisation as important enablers of DH transformation and future platform formations. The paper shows that AI/ML can support lower-temperature, more efficient, customer-oriented, and data-driven DH systems through improved control, analytics, fault detection, predictive maintenance, demand-side management, and optimisation. It contributes to RQ1 by showing that transformation in DH involves a shift from infrastructure-centred operation toward more process- and service-oriented value creation. It contributes to RQ2 by showing that ML-based innovation requires external search and cross-disciplinary collaboration with actors possessing capabilities in data science, IoT, sensors, control systems, software, and customer interfaces.

The paper also identifies a mismatch between current ML research (in 2021) and the needs of the DH industry. While much research focuses on forecasting, several more important transformation challenges remain underexplored, including network control, substation performance, secondary-side data, customer-side behaviour, and predictive maintenance. This strengthens the thesis argument that radical exploration in DH is not only about adopting new technologies, but about aligning technologies, data, business models, organisational capabilities, and external partners.

4.3 Shifting between complementor and supplier relations in digital product-service system innovations

The paper has been submitted to a peer-reviewed journal.

Authors. Håkan Knutsson, Magnus Holmén.

Purpose. The purpose of this paper is to explain how a resource-constrained service-oriented firm searches for and engages external partners, and why and when it shifts between complementor and supplier relations during the development of a digital product-service system.

Findings. The study shows that complementor and supplier relations are not static but may change repeatedly during the innovation process as the nature of the problem, technological interdependencies, and the focal firm's capabilities evolve. Under high uncertainty and resource constraints, complementors are particularly valuable because they provide access to complementary technologies and capabilities and enable relatively rapid and low-cost cognitive search for value expansion. As unresolved technical problems become more specific and interdependencies increase, experiential learning may enable the focal firm to better specify requirements and shift toward a supplier relationship in order to gain greater ownership, control, and predictability. In line with research on complex problem solving, innovative search may therefore proceed through consecutive stages rather than through one stable collaboration form (Baumann & Siggelkow, 2013). The study also identifies strategic risks: downstream complementors may become competitors because they possess complementary assets and technologies close to the focal firm's offering. Later in the process, improved complementor capabilities or high supplier costs may again motivate a return to complementor relations, creating a pendulous movement between the two relationship forms.

Contribution to the thesis. Paper III contributes to the thesis by explaining how radical exploration is organised through changing inter-firm relationships. The paper shows that when a technology-based actor develops a digital product-service system for predictive maintenance in collaboration with a district heating operator,

innovation search shifts from local and experience-based problem solving toward external and technologically distant and cognitive search. The paper identifies how choices between complementors and suppliers are shaped by complementarities, technological interdependence, resource constraints, the need for control, and the risk of creating competitors. In doing so, it provides a micro-level explanation of how external search unfolds in practice and how early ecosystem-like relations emerge around digital innovation in district heating. The paper therefore strengthens the thesis argument that radical exploration in mature infrastructure sectors is often distributed across networks of actors rather than organised within individual incumbent firms.

4.4 From islands to platforms: Innovation pathways for district heating firms across Europe

The paper was published in 2025 in Energy Research and Social Science (https://doi.org/10.1016/j.erss.2025.104317)

Authors. Håkan Knutsson, Magnus Holmén, Eugenia Perez-Vico.

Purpose. The purpose of the paper was to understand how DH firms innovate at the DH energy-system level to create and deliver new value by changing their technological and inter-firm engagements and organisational boundaries.

Findings. The cross-case analysis identifies three innovation pathways through which DH firms and entrants change technological and inter-firm relationships and, in doing so, alter the organisation of value creation. In the first pathway, incumbent firms incrementally adapt the existing hierarchy-based DH system through measures such as market-based pricing, digital services, and closer customer integration. These changes may create additional value for customers and suppliers, but attempts to expand the offering further, for example by adding cooling services, can be difficult to scale because of organisational inertia and lock-in to established structures. In the second pathway, new entrants establish downstream platforms that are closely integrated with customer buildings while using incumbent DH infrastructure as a complementor, creating more ecosystem-like configurations in which value is jointly created across organisational boundaries. In the third pathway, entrants develop independent heating and cooling platforms that may substitute incumbent DH, district cooling, or gas-based systems and thereby challenge or displace established infrastructure providers. Across the three pathways, innovation increasingly depends on integrating DH, heat pumps, cooling, storage, digital services, and customer-side resources through changing actor roles, organisational boundaries, and inter-firm configurations.

Contribution to the thesis. Paper IV contributes to the thesis by providing the main empirical analysis of how district heating firms transform value system configurations through innovation. Based on seven European cases, the paper identifies three innovation pathways: incumbent improvement within existing hierarchy-based value systems, collaborative entry where new platforms complement incumbent DH systems, and disruptive entry where entrants establish heating and cooling systems that challenge incumbent gas, DH, or DC systems.

The paper contributes to RQ1 by showing that DH transformation is not limited to incremental technical improvements, but increasingly involves integration of district heating, cooling, heat pumps, storage, waste heat, customer-side assets, and digital services. It contributes directly to RQ2 by showing how DH firms, entrants, property owners, municipalities, and technology suppliers collaborate or compete in changing value system configurations. Paper IV therefore provides central empirical support for the thesis argument that transformation in district heating occurs through changing actor roles, organisational boundaries, and emerging ecosystem and platform-based coordination mechanisms.

4.5 Ecosystems, capital structure, and entrepreneurial action

The paper was published in 2025 as a chapter in the RESEARCH HANDBOOK ON AUSTRIAN ECONOMICS IN MANAGEMENT AND ENTREPRENEURSHIP, by Edgar Elgar Publishing Ltd. (https://doi.org/10.4337/9781035341870)

Authors. Magnus Holmén, Rögnvaldur J. Saemundsson, Håkan Knutsson.

Purpose. The purpose of the chapter was to understand how entrepreneurial action following the introduction of new capital resources can reinforce or transform ecosystem-based value systems into hierarchy-based or market-based configurations (Jacobides et al., 2018).

Findings. Building on ecosystem theory (Adner, 2017; Jacobides et al., 2018) and Austrian capital theory, the paper conceptualises ecosystems as value systems in which a focal firm and complementors jointly contribute to a common value proposition for the final customer. Drawing on Lachmann (1956), the capital structure is understood as a changing structure of means–ends relationships that both shapes and is shaped by entrepreneurial action. To connect Austrian capital theory with the ecosystem literature, Menger's distinction between goods of different orders is extended to include knowledge of different orders (Menger, 1996). The introduction of a new capital resource may reinforce an existing ecosystem or contribute to its transformation toward a hierarchy-based or market-based value system. The paper identifies three possible evolutionary trajectories following such an introduction, with the direction of transformation depending on three characteristics of the new capital resource: knowledge abstraction, multiple

specificity, and accessibility. These characteristics influence the possibilities for recombination, entry, and entrepreneurial action and thereby shape complementarities, actor roles, and the organisation of value creation over time.

Contribution to the thesis. Paper V contributes to the thesis by providing a conceptual explanation of how value system configurations may change following the introduction of new capital resources. By combining ecosystem theory with the Austrian theory of capital, the paper shows how entrepreneurial action can transform the relationships between focal firms, complementors, entrants, and customers. In the district heating context, customer-side heat pumps, digital technologies, sensors, analytics, automation, and platform interfaces can be understood as new capital resources that enable new combinations of heating, cooling, storage, flexibility, data, and customer-side optimisation.

The paper strengthens the thesis argument that transformation in district heating is not only a technological process, but also a configurational one. It explains why radical exploration may reinforce the existing hierarchy-based value system, support emerging ecosystem-based coordination, or lead to market-based substitution. The direction depends on the knowledge abstraction, multiple specificity, and accessibility of the new capital resource. Paper V therefore contributes mainly to RQ2 by explaining how entrepreneurial action and external actors transform value system configurations, and secondarily to RQ1 by clarifying why competition in heating increasingly occurs between value systems rather than individual technologies.

5. Discussion

This section synthesises the findings from the five appended papers and discusses them in relation to the theoretical background in Section 2. The aim is to develop an understanding of how DH firms transform under conditions of energy transition, how they engage in radical exploration with external partners, and how these processes may reshape established value system configurations.

Section 5.1 addresses the first research question by discussing what characterises transformation and innovation in the DH sector. It shows how innovation remains strongly shaped by path dependen, exploitation-oriented search, and hierarchy-based value systems. Section 5.2 addresses the second research question by analysing patterns of radical exploration and external search. These patterns differ in technological distance, actor constellations, customer involvement, and governance arrangements, compared to the "mainstream" search in the DH sector.

Section 5.3 extends the discussion by applying the structural lens of value systems, especially in terms of ecosystems, and platforms. It considers how new capital-resource configurations, digitalisation, customer-side technologies, and platform-based arrangements may challenge the traditional DH model, while also introducing new governance trade-offs. Taken together, the section argues that transformation in DH is not only a technological process, but also a matter of how innovation search is organised, how external partners are involved, and how value creation is coordinated across firms.

5.1 Transformation and innovation in the DH industry

This section addresses the first research question: what characterises innovation in the DH sector under conditions of energy transition? Revisiting the literature discussed in Section 1, DH firms in Europe can be characterised as predominantly exploitation-oriented, focusing on incremental improvement within established technological and organisational architectures. The empirical material in this thesis largely confirms this assessment. Transformation under conditions of energy transition is observable, but it is gradual, uneven, and structurally constrained. Path creation, i.e. the breaking of path dependence remains difficult, not only in the DH industry but also in heat supply more broadly, particularly where incumbent systems depend on gas and oil infrastructures.

This does not mean that DH firms lack technical competence. On the contrary, heating provision is technically demanding and highly context dependent. Wesche et al. (2019) describe heating as a configurational industry, in contrast to technologies such as solar PV and wind power, which have developed more generic and globally scalable designs. DH systems must be adapted to local buildings, climate conditions, urban density, legacy infrastructure, heat sources, ownership structures, regulatory settings, and customer requirements. This configurational character helps explain why innovation in DH often takes the form of local adaptation, engineering-based problem solving, and system optimisation rather than rapid diffusion of standardised solutions. The DH sector is also structurally fragmented10, consisting of many relatively small and locally embedded operators. This fragmentation limits the resources available for R&D, reduces opportunities to accumulate specialised innovation capabilities, and makes it more difficult to scale and diffuse exploratory initiatives across firms. As a result, radical exploration is often dependent on suppliers, research programmes, consultants, or collaboration with external actors rather than being organised internally by individual DH firms.

Across the empirical material, DH firms tend to rely heavily on public policy instruments, subsidies, and regulatory protection before undertaking major changes. These investments typically concern large-scale production assets rather than exploratory innovation initiatives. Firms respond to incentives such as subsidies and grants for new production resources, including biomass boilers and large-scale heat pumps, which are modular and relatively easy to implement within incumbent DH systems. However, they are more reluctant to engage in complex business models involving third-party heat suppliers, customer-side integration, or unfamiliar external partners. Instead, they often choose technically manageable investments that allow them to remain in control within the established hierarchy-based value system.

This creates a paradox for DH transformation. Regulation and public ownership have historically been important for protecting long-term infrastructure investments, securing reliability, and supporting climate-policy objectives. At the same time, regulation may reduce competitive pressure and weaken incentives for more radical exploration. From a Schumpeterian perspective, regulation can limit creative destruction and reinforce incumbent trajectories (Aghion et al., 2009). Heat pumps may represent a potential source of creative destruction for incumbent heat suppliers, including DH/DC firms, gas network operators, and heating oil suppliers. However, the empirical material contains relatively few examples of

[10] The large number of DH operators in Europe, compared with, for instance, the smaller number of power transmission system operators in electricity, further contributes to fragmentation and limits the potential for scaling breakthrough innovations.

innovation that directly addresses the competitive threat from electrification and individual heat pumps. The tension between regulation, monopoly protection, competition, innovation, and scalability can therefore be understood as a paradox in the sense of W. K. Smith and Lewis (2011): too little competition may slow innovation, while too much competition may undermine incentives for long-term infrastructure investment.

A way to characterise the distribution of innovation attempts in the sector is provided by Figure 3, which should be read as an analytical map of the sector's solution landscape rather than merely as a descriptive categorisation of innovation activities. In line with Ganco et al. (2020), the figure illustrates how different innovation opportunities are distributed across levels and domains of the DH system. It also situates the empirical findings within a broader multi-level perspective on socio-technical transformation (Frank W Geels et al., 2017). At one level, supportive and forward-looking regulation may enable transformation. At another, corporate policies, such as international procurement and selection of competitive solutions may support innovation and scaling. Further upstream and downstream search may open new opportunities beyond the incumbent hierarchy-based structure. End-to-end digital and technical integration from production to end-users may enable lower system temperatures, combined heating and cooling, energy savings, anomaly detection, demand-side flexibility, and new customer value. Finally, new methods of internal efficiency, asset management and operational excellence may support the futureproofing of existing infrastructure.

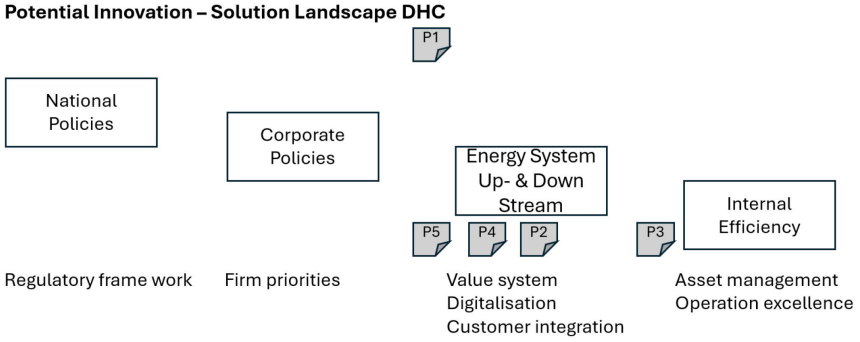

Figure 3. Different levels of potential solution landscapes of DH transformation, innovation and improvement. The vertical perspective represents four levels of analysis. Paper 1-5 are plotted. Paper 1, the systematic literature review, covered the entire solution landscape, while the papers 2-5 focused on firm level DH energy system and internal firm efficiency.

The appended papers are plotted in Figure 3 to show how they relate to different parts of this solution landscape. Paper I maps the research field and shows how DH research has mainly focused on heat supply, system optimisation, policy instruments and environmental impact, the two upper levels in figure 3, while firm-level innovation, management challenges, customer relations, asset management,

and inter-organisational collaboration remain underexplored. Paper II adds a digitalisation perspective by showing how machine learning may support planning, forecasting, optimisation, monitoring, control, and operational efficiency and decision-making in DH. However, it also illustrates a broader challenge: the value of digital technologies depends not only on technical algorithms but also on data access, organisational capabilities, customer-side information, and collaboration between DH operators, technology suppliers, software firms, researchers, and property owners.

The dominant habit in Figure 3 is nevertheless local search within the established hierarchy-based value system and reliance on public policies. Consistent with the analytical framework in Section 2.6, search in DH firms is predominantly experiential and local. Firms rely on established suppliers, familiar technologies, accumulated engineering knowledge, and feedback from prior choices. This backward-looking search is consistent with the literature on experiential learning and search (Gavetti & Levinthal, 2000; Laursen, 2012; Levitt & March, 1988). It supports operational reliability and incremental improvement but also reinforces path dependence and limits the scope for more distant experimentation.

The structured literature review in Paper I supports this interpretation. It demonstrates that explicit engagement with innovation theory remains limited in DH research. Innovation is often implicit and framed as technology adoption or system improvement rather than as a process of search, experimentation, organisational change, and value system reconfiguration. Empirically, DH firms have shown strong capabilities in modular adaptation. Historically, fossil-fuel boilers were replaced by biomass-fired units (Ericsson & Werner, 2016), more recently by large-scale heat pumps (Barco-Burgos, Bruno, Eicker, Saldaña-Robles, & Alcántar-Camarena, 2022; Johansson, 2017) and emerging Carbon Capture and Storage solutions (Lindroos et al., 2019). These transitions indicate competence in adopting new components that fit existing system architectures. However, they also suggest a path-dependent development trajectory (Dosi, 1982) dominated by incremental improvement and consistent with earlier findings that industry-level R&D programmes primarily target efficiency gains rather than transformative change (Sernhed, Lygnerud, & Werner, 2018).

The organisation of R&D in the DH sector reinforces this pattern. Due to limited competition between DH firms, national DH industry associations, as well as EU and IEA programmes, operate relatively ambitious joint R&D activities. These programmes resemble forms of open innovation in that common challenges are identified, and solutions are searched for collectively (Dahlander, Gann, & Wallin, 2021; Ebersberger, Galia, Laursen, & Salter, 2021; Laursen & Salter, 2014). The DH sector has a strong tradition of sharing experiences. However, the focus of these activities is often incremental technology improvement (Sernhed et al., 2018), and the fragmentation of the sector into many small operators limits national and international scaling. As a result, search remains largely internally oriented

and focused on similar technologies, rather than externally oriented and technologically distant.

Paper II illustrates what happens when DH firms encounter more distant technological paradigms, such as AI and ML. ML, sensors, IoT, automation, and data analytics may support lower-temperature operation (4GDH), demand-side management, predictive maintenance, fault detection, customer segmentation, and system optimisation. However, Paper 2 also shows that such technologies require new forms of cross-disciplinary cooperation. Successful development depends on interaction between data scientists, domain experts in energy, maintenance, automation and control, organisational experts, DH firms, technology suppliers, and representatives from the building and property sector. This indicates that digitalisation is not only an operational tool; it also challenges the incumbent value system by requiring new organisational interfaces and inter-firm collaboration. In this sense, the digitalisation of DH can become a trigger for broader reconfiguration and customisation, although the empirical material suggests that this potential is still only partly realised.

Taken together, the findings suggest that innovation in the DH sector is best understood as distributed across a solution landscape, with hills representing more optimal solutions and valleys representing less favourable alternatives. The dominant part of this landscape remains characterised by local, experiential search within hierarchy-based value systems. Firms tend to search close to existing technological and organisational positions, relying on established suppliers, familiar technologies, accumulated operational knowledge, and policy-supported investment logics. Such search is efficient when problems are well understood and conditions are relatively stable, and it has supported substantial incremental improvements in efficiency, reliability, and environmental performance. However, it also increases the likelihood that firms remain close to local optima, reinforcing path dependence and making more distant alternatives harder to identify and evaluate. As a result, the scope of exploration remains constrained even when changes in technology, competition, and customer requirements suggest that more distant parts of the solution landscape may contain superior alternatives.

At the same time, the empirical material shows emerging forms of exploration at the boundaries of incumbent systems. These include customer integration, digital product-service systems, predictive maintenance, combined heating and cooling, downstream heat-pump configurations, demand-side flexibility, and platform- and ecosystem-like arrangements involving property owners, municipalities, energy service companies, technology suppliers, and digital actors. These initiatives expand the solution landscape by connecting DH firms to new knowledge domains and external actors. However, they remain unevenly distributed and are often concentrated in a small number of innovative firms or local projects.

The answer to RQ1 is therefore that transformation and innovation in the DH sector are characterised by a combination of strong continuity and selective reconfiguration. The dominant pattern remains incremental, exploitation-oriented, and embedded in hierarchy-based value systems. Yet external pressures from decarbonisation, price on biomass, long-term reduction of combustible waste, increasing cooling demand, digitalisation, ageing infrastructure, electrification and competition from heat pumps are gradually challenging this model. Transformation does not appear as a sudden technological disruption. Here it is better understood as a gradual and uneven reconfiguration of value systems, where incremental innovation continues to dominate but exploratory initiatives increasingly appear at the boundaries of incumbent systems.

This overall pattern provides the foundation for Section 5.2, where the focus shifts from the general character of transformation in the DH sector to the specific cases in which DH firms and their partners move beyond incremental improvement and engage in more radical forms of exploration.

5.2 Radical exploration and external search for innovation

The answer to the first research question shows that transformation in the DH industry is characterised by awareness of the need for change but limited innovation beyond incremental improvements. Most firms adopt a wait-and-see approach, relying on external funding to finance capital-intensive investments. However, several cases in this thesis represent exceptions, displaying more radical forms of exploration and external search. These cases address the second research question: How do district heating firms engage in exploration with external partners, and how does this transform value system configurations?

While innovation in the DH industry remains predominantly incremental and path dependent, the empirical cases reveal distinct pockets of radical exploration. These cases illuminate how DH firms and their partners search beyond established technological domains, organisational boundaries, and value systems when incremental innovation proves insufficient. Rather than reiterating individual results, the focus here is on synthesising overarching patterns that explain how innovation search is organised, how inter-firm relationships evolve, and how value system configurations shape transformation processes.

Across the cases, external search for innovation can be analysed along four related dimensions: what is developed, how search is organised, who leads the process, and how the search relates to the surrounding value system. These dimensions correspond to differences in 1) technological novelty, 2) organisation of search, 3) actor constellation, and 4) value-system configuration and together distinguish five patterns of radical exploration in the DH industry, discussed below. As will be

shown, the patterns suggest that radical exploration is shaped not only by technological distance and external search, but also by how innovation activities are organised across actors and embedded in different value-system configurations.

When incremental innovation is insufficient and external funding is unavailable, DH firms may face situations characterised by high uncertainty, risk of infrastructure degradation, rising fuel prices, and loss of market share. In such contexts, firms need to shift from exploitation towards exploration (Levinthal & March, 1993; March, 1991). This involves searching beyond firm boundaries and beyond known technologies, referred to as radical exploration (Rosenkopf & Nerkar, 2001), see Figure 1.

Radical exploration can take place in relation to different value systems. In some cases, DH firms remain within the incumbent hierarchy-based value system while searching for distant technologies through new suppliers. In other cases, incumbent firms and new entrants co-create value in emerging platform-based ecosystems, representing a fundamentally different value system configuration.

Based on the empirical material from the papers (see section 3.3.4), ten innovation initiatives involving the selected actors are positioned in five pattern groups in Figure 4. The vertical axis captures innovation characteristics, ranging from new-to-the-world innovation to new combinations of existing modules. All ten innovation initiatives involve radical exploration through search beyond established organisational and technological boundaries. However, they follow different trajectories: some remain within hierarchy-based value systems, some move toward customer integration, and others contribute to emerging platform-based ecosystems.

The innovation initiatives are analysed in the following sections in terms of *what* is developed, *how* innovation search is organised, *who* leads the process, and *why* these shifts occur from a theoretical perspective. The level of analysis is indicated in Figure 3, see the location of the five papers.

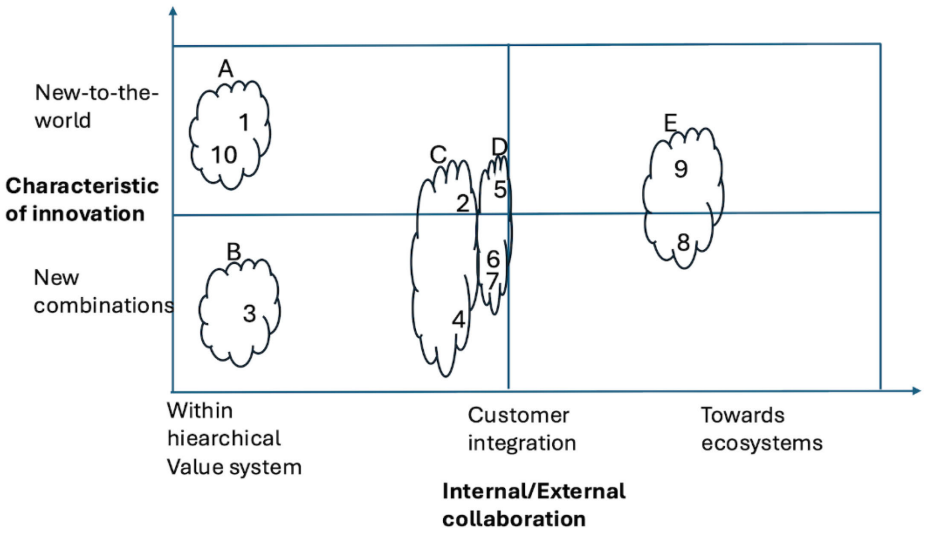

Figure 4. Innovation initiatives in the appended articles, within this thesis, grouped in five groups, based on patterns, trajectories.

There are common characteristics in the five groups, see figure 4 and the following sections. New search processes are frequently triggered by external pressure, such as competition, regulatory changes, technology developments in adjacent industries or policy-driven funding opportunities. Even when search extends beyond traditional boundaries, the firm´s search often remains cognitively anchored in existing systems logics. Firms and their individuals interpret new opportunities through established technical and organisational frames, which constrain the degree of novelty achieved, which refers to bounded rationality (Simon, 1982). New type of collaborations is often structured within traditional contractual arrangements, which limits flexibility and shared risk-taking. Organisational structures, procurement routines, and risk-averse cultures often constrained the scope of experimentation. This refers to organisational resistance to changes according to Nelson and Winter (1982). A recurring pattern in the empirical material is that radical exploration is enabled by individuals or small groups acting as boundary spanners, where different external relations became appropriate at different stages. These actors connect internal operational knowledge with external technological expertise. Overall, radical exploration in DH firms appears yet to be episodic rather than systemic. It emerges in specific projects but does not fundamentally alter the dominant exploitation-oriented logic of the industry.

A central finding from Paper III is that radical exploration is not only defined by technological distance and external search, but also by the changing form of inter-firm relationship through which search is organised. In the case of digital

predictive maintenance, the focal technology firm moved from a service-based offering toward a product-service system by combining its own domain-specific knowledge with external digital technologies. This required the firm to search beyond its existing knowledge base and beyond its established supplier relations. The case shows that external search may unfold through consecutive problem-solving episodes, where different external relations become appropriate at different stages. Complementor relations can be particularly useful when the focal firm lacked resources and needed to access complementary technologies quickly, especially under conditions of cognitive search and uncertainty. However, when technological interdependencies increase, when lock-in emerge, or when a focal firm need stronger control over development, supplier relations are likely to become more attractive despite higher costs. The same process could also move in the opposite direction, as improved complementor capabilities or high supplier costs may make complementor relations preferable again. Such arguments nuance the understanding of radical exploration in the DH sector. It suggests that external search is not a stable organisational arrangement, but a dynamic process in which firms repeatedly reconsider whether innovation should be pursued through suppliers, complementors, customers, or other partners. Radical exploration therefore involves both technological search and governance search: firms must search not only for new technical solutions, but also for suitable forms of inter-firm coordination. This is particularly important for digital innovation in DH, where value creation depends on combining sensors, data, analytics, customer interfaces, and operational knowledge across several firms.

The following sections illustrate how the search and coordination choices take different forms across the five identified patterns, beginning with cases characterised by new-to-the-world product innovation.

5.2.1 New-to-the-world product innovation

The first pattern, upper-left group A in Figure 4 represents initiatves (1, 10) where two DH firms face problems they cannot solve internally or through incumbent suppliers. It is about ageing pipes and increased risk of rupture and severe damages. The DH firms initiate radical exploration by engaging new external technology suppliers, thereby spanning organisational and technological boundaries (Rosenkopf & Nerkar, 2001). Theoretically, this pattern can be explained by a capability mismatch: DH firms, thousands in Europe, are optimised for asset exploitation, not exploration as explained by (March, 1991), while specialised technology suppliers possess the organisational structures and risk tolerance needed for radical innovation and exploration. The shift is thus not a transformation of the DH firm itself, but a strategic outsourcing of exploration, within the incumbent hierarchy-based value system.

The technology suppliers, lacking ready-made solutions, engage in forward-looking cognitive search under uncertainty (Gavetti & Levinthal, 2000; Nickerson & Zenger, 2004). Innovation unfolds through long-term development processes involving multiple subprojects, reflecting a form of "chunky search" (Baumann & Siggelkow, 2013). Some problems are decomposable, while others are very complex, involve high interdependencies, requiring search in rugged solution landscapes (Ganco et al., 2020) and collaboration with additional complementors.

The two cases are similar, one is about developing new digital Product Service Systems (Reim, Parida, & Örtqvist, 2015; Sala, Bertoni, Pirola, & Pezzotta, 2020) with unique measurement technology for condition monitoring and predictive maintenance of DH pipes. The other case is about developing a new material for relining, repairing old, corroded pipes. In the cases, the search for external relations is changing over time and emergence of innovation ecosystems according to Adner (2006); Ganco et al. (2020), with focal actor and upstream and downstream complementors appear.

The resulting innovations represent new-to-the-world products in a mature industry, developed through supplier-user interaction (Lundvall, 1985) and lead-user dynamics (Von Hippel, 2007). From the DH firms' perspective, these innovations are attractive because they can be adopted without changing the incumbent hierarchy-based value system. From the suppliers' perspective, the innovations have potential for diffusion (Rogers, 2010) to many users under the emergence of a dominant design (Wesche et al., 2019), not as in the DH firms that are dominated by a configurational logic, with repeated engineering due to minor differences and variation in the connection to customers and DH firm routines.

5.2.2 Production and city focus, synergies and symbiosis

The second pattern, lower-left group B of firm (3) in Figure 4 represents an incumbent DH firm focusing on production optimisation and city-level synergies. External search in this case is oriented toward back-end collaboration with other municipal utilities in wastewater treatment and waste handling. Previous innovations include heat recovery from treated wastewater by use of large heat pumps, CHP and heat driven district cooling from waste incineration. Next innovation is to invest in Carbon Capture and Storage (CCS) from waste incineration. CO2 emission from incineration of plastics is captured, avoiding emission fee. Bio-based waste is also incinerated, with CO2 captured meaning negative CO2 emissions and an opportunity to get paid for the capture of biogenic CO2.

Search is primarily experiential and backward-looking, based on recombination of known technologies and guided by consultants and technology suppliers from other industries (oil & gas) according to Pavitt (1984) taxonomy for supplier led

industries. While the configuration resembles multi-sided markets (Jia et al., 2019) or industrial ecosystems (Burström et al., 2024), governance remains hierarchical, with municipalities often acting as focal actors.

This pattern persists because it aligns with existing organisational experience and ownership structures. Municipal coordination reduces transaction costs and risk, making capital-intensive innovation feasible, while limiting incentives for more radical exploration.

5.2.3 Customer integration

The third pattern, centre-left group C in Figure 4 includes firms (2, 4), characterised by increased customer integration while maintaining the hierarchy-based value system.

The first DH firm integrates upstream with a surplus heat provider, interchanging heating and cooling services, and downstream with heating customers in a new built city district, developing a large-scale 4GDH network, with buildings adapted to accept lower supply temperatures. The relation with the external supplier of waste heat, in exchange of receiving cooling services, is a sort of prosumer relation according to (Zafar et al., 2018).

The second DH firm develops a digital platform, that integrates heat and power production with customer buildings, a so-called end-to-end integration. The digital platform integrates building-level data, enabling energy savings, demand-side flexibility, and predictive maintenance and anomaly detection.

External search in these cases involves close collaboration with both incumbent and new technology suppliers and iterative experimentation with customers.

The shift toward customer integration is driven by competitive pressure in a deregulated market and can be explained by theories of customer integration and service-dominant logic (Martinelli & Tunisini, 2019; Wilson, Zeithaml, Bitner, & Gremler, 2016). From an innovation perspective, this shift widens the solution landscape downstream (customers) as well as upstream (producers), enabling experiential learning that was previously inaccessible to DH firms focused primarily on production (Ganco et al., 2020).

Paper III illustrates this pattern at the micro level. The development of predictive maintenance transformed a manual technical service into a digital product-service system, requiring sensors, IoT hardware, data handling, analytics, and customer-facing interfaces to be combined. This was not achieved through internal development alone, nor through a stable supplier chain. Instead, the innovation process depended on changing relations with complementors and suppliers as different technological problems emerged. The case therefore shows how

digitalisation and customer integration push DH-related innovation beyond the traditional hierarchy-based supply-chain system, while remaining closely connected to incumbent infrastructure and operational problems.

5.2.4 Entrants, customer integration, new configuration

The firms (5, 6, 7), in the centre-right group D in Figure 4 represents cases where new entrants substitute or replace incumbent distributors of district heating, district cooling, or gas. In these cases, one hierarchy-based value system is disrupted and replaced by another hierarchy-based value system in line with value system definitions by Jacobides et al. (2018), rather than evolving incrementally from within. All three firms are operating platform-alike new systems, with multiple market sides, for instance including cooling to some customers that gives heating to other customers. Firms strive for temporary monopolies (McIntyre et al., 2021). Firms operating multisided platforms (Jia et al., 2019) are aiming for "winner-takes-all" position and networks effects, which is strengthening the platform and up to a certain degree giving higher value to the customers. However, the customers must have a choice in the longer term. Otherwise, regulation of platforms is needed (Cennamo et al., 2025). Integrating heat pumps into a 5GDHC-network, a digital thermal DH network, is a type of strategy, enveloping the threat from individual heat pumps.

In two cases, gas distribution is replaced by fifth-generation district heating and cooling (5GDHC), based on decentralised heat pumps installed in customer buildings. In a third case, an incumbent DH and DC system is replaced by a new entrant introducing a decentralised configuration of 5GDHC. The technologies involved are largely proven, but innovation arises through new system configurations, combinations and business models, combined with stronger customer integration. In contrast to conventional DH, the 5GDHC system can provide heating as well as cooling, which also many building level heat pump installations can do.

External search in these cases is characterised by recombinative exploration, where known technologies are combined in new ways. Search is guided by experiential learning and pilot projects that limit downside risk. The actors leading the search are large, resourceful entrants willing to assume financial risk.

From a theoretical perspective, these cases reflect Schumpeterian creative destruction (Schumpeter, 2008) and the Austrian School of Economics, which is discussed in Paper V. By introducing new capital resources (heat pumps), and new system architectures, entrepreneurial action is triggered (Aghion et al., 2009) where entrants gain leverage over incumbents (Lachmann, 1956) and moving closer to end customers in the order of goods (Menger, 1996), compared to the incumbents. The decentralised heat pump configurations can also be interpreted as

a step towards a dominant design with greater scalability and lower engineering complexity (Wesche et al., 2019) than typical DH systems.

At the same time, these cases reveal limitations. Heat pumps typically operate within a market-based value system, requiring individual customers to invest, operate, and maintain assets. The Product–Service System (PSS) perspective (Goedkoop, Van Halen, Te Riele, & Rommens, 1999; Tukker, 2004; Tukker & Tischner, 2006), explained in Paper III, adopted by DH operators, suggests that combining products and services - supported by digitalisation and servitisation (Gebauer, Paiola, Saccani, & Rapaccini, 2021) - could mitigate these limitations and enhance customer value.

5.2.5 Emerging new ecosystems

The fifth pattern, the rightmost group E of firms (8, 9) in Figure 4 points toward the emergence of ecosystems, as conceptualised by Jacobides et al. (2018, 2024), with focal firm and complementor. While the technical configurations in these cases share similarities with those in Section 2.2.4, a critical difference lies in *who* leads the innovation search and *why*.

These configurations integrate heating, cooling, electricity, energy saving & storage, and sometimes rainwater services at the city district, block level, from a few buildings up to about 50 buildings. Value is created for many actors, upstream (production) as well as downstream (end-users).

Theoretically, this shift reflects attempts to overcome value system misalignment between DH firms and building owners.

In these cases, property owners are the primary drivers of innovation – focal firms, motivated by rising energy costs and increasing demand for cooling. DH providers adapt to this new configuration rather than acting as focal innovators.

Geothermal boreholes are used as combined sources and storage for heating and cooling, and energy is shared locally among multiple buildings.

External search is distributed and multi-actor, involving property owners, DH firms, technology suppliers, and municipalities. The search process addresses complex, non-decomposable problems that cannot be solved within a single organisation, but need collaborative arrangements (Nickerson & Zenger, 2004). From a theoretical perspective, this reflects innovation in rugged solution landscapes (Kauffman, 1993), where progress, that is finding solutions, depends on coordinated experimentation across multiple actors (Ganco et al., 2020).

These configurations resemble energy communities (Fouladvand, Ghorbani, Mouter, & Herder, 2022), although they extend beyond electricity sharing to include heating, cooling, storage, and water-related services. Governance shifts

from hierarchical control to ecosystem coordination, with property owners acting as focal firms and DH firms as upstream complementors.

5.2.6 Summary of the findings on patterns

The preceding sections identified five patterns of radical exploration in the district heating industry. These patterns differ in terms of what triggers the search process, how external search is organised, who leads the exploration, what type of search is involved, and what innovation outcome follows. Taken together, the patterns provide an answer to RQ2 by showing that DH firms do not engage in exploration with external partners in one uniform way. Rather, exploration is contingent on the nature of the problem, the technological distance involved, the actor constellation, and the prevailing value system configuration.

Table 5 summarises the five patterns. It shows how external search may be directed upstream toward suppliers and technology providers, downstream toward customers and building owners, horizontally across municipal or industrial utilities, or across several market sides of an emerging ecosystem. It also distinguishes between experiential and cognitive search, between more decomposable and non-decomposable problems, and between different governance forms, ranging from hierarchy-based coordination to market-based substitution and ecosystem-based collaboration. These dimensions operationalise the broader differences in technological distance, actor constellation, organisation of search, and value-system configuration discussed above.

Table 5. Patterns of radical exploration, external search for distant technology, from the cases (RQ2)

Pattern of radical exploration	Trigger for search	HOW external search is conducted	WHO leads the search	Type of search (theory)	Resulting innovation outcome
A. New-to-the-world product innovation (within hierarchical value system)	Acute technical problems unsolvable internally (e.g. ageing infrastructure, rupture risk)	Boundary-spanning search for *distant technology* beyond incumbent suppliers; long-term collaboration with new entrants; problems decomposed into subproblems ("chunky search")	External technology suppliers, guided by focal DH firm as problem owner	Radical exploration across technological and organisational boundaries (Rosenkopf & Nerkar, 2001); forward-looking cognitive search (Gavetti & Levinthal, 2000); non-decomposable problem solving	New-to-the-world products (e.g. predictive monitoring, novel relining materials), later diffused across DH sector
B. Production and city-level synergies (within hierarchical value system)	Need for decarbonisation, efficiency gains, and asset optimisation at city level	Experiential, backward-looking search within known technological domains; recombination of proven technologies via consultants, suppliers and public programmes	Incumbent DH firm and municipal owner	Supplier driven search (March, 1991); recombinative innovation; incremental exploration	Recombinative innovation (waste to heat, Carbon Capture and Storage - CCS, industrial symbiosis)
C. Customer integration and digitalisation (within hierarchical value system)	Competitive pressure, customer loss, and demand for flexibility and efficiency	Joint exploration with customers and new suppliers; co-development of digital PSS platforms; iterative experimentation across organisational boundaries	Incumbent DH firm, in collaboration with suppliers and key customers	Hybrid search combining experiential and cognitive elements; boundary spanning downstream and upstream; widening solution landscape (Ganco et al., 2020)	Customer-integrated and digital system innovation within the incumbent hierarchy-based value system : 4GDH systems, demand-side flexibility
D. Entrants and re-configuration of hierarchical value systems	Market liberal-isation, substitution threats (gas → heat pumps), infrastructure renewal	Search through recombination of proven technologies with new business models; pilot projects to limiy downside risk	Large, resourceful new entrants acting as risk absorbers	Exploratory recombination; Schumpeterian creative destruction; experiential learning at system level	New DHC/5GDHC configurations, decentralised heat pump systems
E. Emerging ecosystems	Misalignment between DH firms and building owners; rising demand for integrated heating, cooling, and energy services	Distributed, multi-actor search across upstream and downstream partners; coordinated experimentation within emerging ecosystem or platform-like configurations.	Property owners or energy communities as focal firms; DH firms as complementors	Ecosystem-level search (Adner, 2017); innovation platforms (Jacobides et al., 2024); search in rugged solution landscapes (Kauffman, 1993)	Emerging ecosystems integrating heating, cooling, heat pumps, storage, electricity and customer-side energy resources.

Radical exploration is commonly understood as double boundary-spanning search: firms search beyond their existing technological knowledge base and beyond their organisational boundaries (Rosenkopf & Nerkar, 2001). The findings of this thesis support this understanding but also extend it. The five patterns show that radical exploration in infrastructure-based industries is shaped not only by technological distance, but also by how value creation is organised across customers, suppliers, entrants, and complementors.

A cross-comparison of the five patterns reveals three main findings. First, the locus of innovation gradually shifts from the core production activities of the incumbent DH firm toward the boundaries of the value system, where innovation increasingly depends on interaction with customers, entrants, complementors, and other external actors. As the locus of innovation moves outward, the initiative and influence over exploration also become distributed beyond the incumbent firm.

Second, the actor leading exploration therefore changes across the patterns, from incumbent DH firms and established suppliers toward entrants, property owners, and ecosystem focal actors. Third, the governance of search becomes increasingly complex as innovation moves from component-level problem solving toward customer-integrated, digital, and ecosystem-based configurations.

In pattern A, radical exploration remains embedded within the incumbent hierarchy-based value system. The DH firm acts primarily as a problem owner, while specialised external suppliers conduct much of the cognitive and technological search required to solve narrow but complex infrastructure problems. Exploration is therefore externalised, but not necessarily transformative for the incumbent firm's value system. Innovation occurs upstream, often at the component or subsystem level, and may later diffuse across the DH sector.

Pattern B also remains within the hierarchy-based value system, but the search process is broader and more city-oriented. Innovation is organised through recombination of existing technologies, municipal capabilities, public programmes, consultants, and established suppliers. This pattern reflects exploration close to existing capabilities and institutional arrangements. It may generate important improvements in decarbonisation, efficiency, waste heat use, or industrial symbiosis, but it rarely challenges the basic organisation of the DH value system.

In Group C, innovation moves closer to the customer interface. External search expands downstream and involves new forms of collaboration with building owners and technology suppliers. Although governance remains hierarchical, the scope of experimentation increases as firms integrate digital platforms with customer, similar to concepts of digital Product Service Systems (Sala et al., 2020) and customer-level data into their operations.

A more fundamental shift appears in pattern D and E, where exploration no longer occurs primarily within the incumbent value system. Instead, new actors and organisational configurations reshape how innovation is organised. The DH dilemma is more explicitly addressed, in these constellations. In contrast to other utility systems such as gas, electricity and water, DH system efficiency is directly dependent on each customer, small as well as large. Unlike many other utility systems, DH performance is directly affected by customer-side conditions. System efficiency improves when customers can accept lower supply temperatures and extract more heat from each unit of flow, thereby reducing return temperatures. Patterns D and E address this interface more directly by moving beyond the traditional sale of heat as a commodity toward more integrated energy-as-a-service models.

In pattern D, new entrants (disruptors) develop alternative infrastructure configurations that compete with existing utility systems. These cases illustrate forms of Schumpeterian creative destruction, where new combinations of technologies and business models substitute previously dominant infrastructures, but maintaining a configuration of hierarchy-based new value system. This group has the close customer relation in common with group C and E.

Pattern E represents the most far-reaching transformation identified in the empirical material. Here, innovation is organised through emerging ecosystems, where property owners act as focal actors coordinating complementors in emerging ecosystems. The DH firm becomes one participant, rather than the central orchestrator or focal firm of the value system. These platforms have similarities with Energy Communities, constellations formed to share electric power (Fouladvand et al., 2022), which also the focal firms in group E are doing, but they also share and store heating and cooling.

Taken together, the five patterns or model indicate that radical exploration in infrastructure industries rarely follows a single organisational model. Instead, exploration emerges through multiple configurations ranging from supplier-led innovation within hierarchical value systems to distributed experimentation in ecosystems. This finding extends existing research on exploration and search by showing that the governance of search (Nickerson & Zenger, 2004) is closely tied to value system configuration (Jacobides et al., 2018). In mature infrastructure sectors characterised by heavy assets, long investment cycles, and regulatory constraints, radical exploration is often externalised, delegated, or initiated by actors outside the incumbent firm.

As a result, transformation does not necessarily require incumbents to abandon their existing organisational structures. Rather, innovation frequently occurs at the boundaries of the value system, where new actors, technologies, and collaboration forms gradually reshape the solution landscape.

The findings also help explain why transformation in the district heating sector tends to be gradual and uneven. Because exploration is often project-based and externally organised, it remains episodic rather than systemic. Incumbent firms continue to prioritise exploitation and asset optimisation, while more radical experimentation occurs at the margins of the system.

5.3 Looking back, looking forward – competition and collaboration between firms in different value systems

The empirical findings indicate that the existing hierarchy-based value system in the DH industry creates structural constraints for innovation. DH firms traditionally operate as vertically integrated utilities with strong control over assets and operational processes. This configuration has historically ensured reliability and efficiency but may limit flexibility and openness toward new forms of value creation.

The hierarchy-based model emphasises ownership and control of key assets, long-term planning horizons, and risk minimisation, reflecting an exploitation-oriented organisational logic. Customer relations are traditionally limited and, in many countries, constrained by price regulation (Gorroño-Albizu & de Godoy, 2021; Odgaard & Djørup, 2020). Such characteristics are well aligned with incremental improvement but less suited for exploratory initiatives requiring distributed experimentation and shared value creation.

A central challenge identified in the empirical material is the misalignment between emerging innovation opportunities and the dominant value system, which illustrates tensions between exploration and exploitation at the system level. The findings suggest that the slow transformation of the heating sector cannot be explained by technological constraints alone. Rather, it reflects a combination of limited external search, and weak integration between producers, distributors and users. While the technical feasibility of decarbonised heating solutions is well established (Connolly et al., 2014; Connolly & Mathiesen, 2014; Lauenburg & Wollerstrand, 2014; H. Lund, 2018; H. Lund, Duic, Østergaard, & Mathiesen, 2018), the organisational and inter-organisational conditions required for their diffusion and scaling remain underdeveloped. For example, integration of third-party heat sources, demand-side (customer) flexibility, and digital service offerings require coordination across multiple actors with partially overlapping roles and incentives, thereby increasing interdependence within the value system. However, existing governance structures and contractual practices are often not designed to support such distributed configurations, as they are rooted in hierarchical control rather than ecosystem coordination. This misalignment may

explain why many exploratory initiatives remain limited in scale and duration, and why search processes tend to revert to incremental adaptations.

From the perspective of RQ1, transformation and innovation in the DH sector are characterised by a strong reliance on incremental innovation within incumbent hierarchy-based value systems (Jacobides et al., 2018, 2024). This mode of innovation has historically been effective under relatively stable conditions, supported by regulation and public policy (Salite et al., 2024), but it struggles to accommodate the uncertainty, complexity, and cross-sector interdependencies associated with the energy transition, where customers get alternative offerings. The empirical cases demonstrate that when these conditions intensify—through competition, technological discontinuities, or changing customer demands—incremental innovation becomes insufficient, and new forms of external search are required (Levinthal & March, 1993; March, 1991).

From the perspective of RQ2, the thesis shows that external search for innovation in the DH sector is heterogeneous and contingent, rather than uniform, with only a few firms active. Firms do not simply "open up" innovation in a generic sense. Instead, they engage in distinct patterns of search (Gavetti & Levinthal, 2000; Laursen, 2012; Rosenkopf & Nerkar, 2001) shaped by the nature of the problem, the availability of resources, competitive pressure, and the prevailing value system. Radical exploration occurs selectively, often at the boundaries of the incumbent organisation, and frequently through collaboration with external partners that possess complementary capabilities (Ganco et al., 2020).

5.3.1 Competition between value systems

An important implication of the findings is that competition in the heating sector increasingly takes place between value systems rather than between individual technologies. District heating, individual heat pumps, and emerging hybrid heating and cooling solutions are embedded in fundamentally different organisational logics. Traditional DH systems operate within hierarchy-based value systems, characterised by central coordination, long-term investment horizons, collective optimisation, and strong control over production and distribution. This configuration reinforces path dependence (Dosi, 1982). Individual heat pumps, by contrast, are typically embedded in market-based value systems, where investment, operation, maintenance, optimisation, and risk are decentralised to individual property owners. These contrasting organisational logics can be understood through the concept of value systems developed by Jacobides et al. (2018), which also connects to the governance structures through which firms coordinate and solve complex problems (Nickerson & Zenger, 2004).

This distinction helps explain why the transformation of urban heating cannot be understood as a simple competition between district heating and heat pumps as

technologies. Each value system is effective in solving certain coordination and investment problems, while at the same time creating new constraints and dependencies. Market-based solutions may diffuse rapidly and offer flexibility for individual users, but they also decentralise responsibility for investment, operation, maintenance, optimisation, and technical competence to individual property owners. Hierarchy-based DH systems, by contrast, enable system-level optimisation, fuel flexibility, and integration of surplus heat through coordinated infrastructure and centralised control, but they may also become inward-looking, slow to adapt, and constrained by established technologies, routines, and path dependence. The empirical findings therefore suggest that neither value system alone is sufficient to address the increasing complexity of heating under conditions of decarbonisation, electrification, growing cooling demand, and increasing customer-side activity. Papers III and IV empirically illustrate how innovation can involve movement between, or recombination of, different value-system configurations, while Paper V develops this argument conceptually by showing how the introduction of new capital resources, such as machine learning, heat pumps, development tools, or machine tools, may trigger entrepreneurial action and contribute to the reconfiguration of existing value systems.

The transformation of DH firms can therefore be understood as a configurational process with a common incumbent starting point but several possible pathways, as illustrated in Figure 5. The starting point is the incumbent DH firm operating within a hierarchy-based value system, where innovation is primarily incremental and focused on exploiting existing assets and capabilities. External pressures associated with the energy transition — including decarbonisation, reduced reliance on combustible fuels, electrification, increased cooling demand, and the diffusion of heat pump technologies — challenge the viability of existing value system and create incentives for strategic change.

The introduction of new capital resources, such as customer-side heat pumps and digital technologies, then creates opportunities for entrepreneurial action by enabling new combinations of complementary assets. Distributed heat pumps installed in customer buildings, as discussed in Paper IV, combined with digital technologies such as sensors, IoT, automation, predictive analytics, AI, and machine learning, as discussed in Paper II, can be understood as a new capital-resource configuration. These resources create possibilities for new combinations of heating and cooling, thermal storage, heat recovery, demand flexibility, and customer-side optimisation. They therefore challenge the traditional boundary between the DH firm and the customer building.

The direction of transformation depends on how these new capital resources are mobilised and by whom. DH firms may envelop heat pumps and digital tools into the existing hierarchy-based value system, collaborate with complementors in emerging ecosystem-based configurations, or lose customers and control to market-based alternatives. These three possible outcomes are illustrated in Figure

5. Thus, competition in the heating sector increasingly concerns who controls the relevant capital resources, who integrates the complementary modules, and where value creation takes place. This interpretation connects the empirical findings of the thesis to Paper V by showing that transformation in DH is not only technological, but also organisational and configurational.

Figure 5. Possible pathways of DH transformation and three alternative value-system configurations. The incumbent pathway is in the middle, continuation of a hierarchy-based value system. The two alternative pathways represent a disruptive pathway, where a market-based value system replace the incumbent, or an evolution from hierarchy-based system to ecosystem-based value system.

Following Figure 5, the transformative effect of new capital resources depends on how they are combined, accessed, and governed. If customer-side heat pumps, digital tools, or control systems remain strongly dependent on incumbent DH system knowledge, transformation is likely to reinforce the existing hierarchy-based value system. In this case, the DH firm may integrate these resources into its existing organisational logic while maintaining its role as the central coordinator. Innovation then remains primarily an extension of the incumbent value system.

A second pathway is the emergence of ecosystem-based value systems. This becomes more likely when value creation requires complementary knowledge and capabilities distributed across several actors, while the complementarities remain

sufficiently specific to require coordination. In such cases, DH firms may need to collaborate with surplus heating and cooling providers, technology suppliers, installers, digital service firms, property owners, and customers to co-create value. This pathway is particularly important when value creation depends on integrating customer-side assets with network-level optimisation. Such developments are consistent with the literature on ecosystem initiatives in district heating (Peltokorpi, Talmar, Castren, & Holmstrom, 2019; Volkova et al., 2022) and are reflected in the empirical findings of Papers III and IV.

A third pathway is market-based substitution. If customer-side technologies become sufficiently accessible, modular, and generic, customers and entrants may be able to create value without relying on the incumbent DH firm. In such cases, heat pumps, digital control systems, and other building-level solutions may shift value creation away from the DH system and toward a more decentralised market-based value system. This does not mean that heat pumps automatically substitute DH, but it does mean that the competitive threat comes from an alternative value system in which customers, suppliers, and service providers can coordinate without the incumbent DH network operator.

Seen in this way, transformation in DH is not only technological, but also configurational and organisational. The introduction of new capital resources may alter the relationships between DH networks, customer buildings, technology suppliers, digital service providers, and end users. Paper V supports this interpretation by showing how new capital resources can reshape means–ends relationships and create conditions for entrepreneurial action. However, the broader thesis argument is that such transformation depends on how actors organise search, collaboration, and value creation across different value system configurations.

The contribution of this section is therefore to show that competition in the heating sector increasingly concerns the configuration of value creation. DH firms may respond by extending the existing hierarchy-based value system, by engaging in ecosystem-based coordination with complementors, or by facing substitution from more decentralised market-based alternatives. This interpretation connects the empirical findings on external search, complementor and supplier relations, and platform-based innovation pathways by combining contributions from several of the appended papers.

5.3.2 Platform-based ecosystems as an emerging coordination mechanism

The discussion in the previous section suggests that transformation in the heating sector increasingly concerns competition between value system configurations rather than competition between single technologies. Against this backdrop, platform-based ecosystems can be understood as one emerging coordination

mechanism through which DH firms and their partners may respond to increasing technological and organisational interdependence. This interpretation builds on the distinction between market-based, hierarchy-based, and ecosystem-based value systems (Jacobides et al., 2018, 2024). As heating systems become more distributed, digitalised, and customer-integrated, value creation increasingly depends on resources and capabilities located across several independent actors. These include DH firms, property owners, technology suppliers, installers, digital service providers, surplus heat providers, cooling users, and flexibility markets. Such conditions are difficult to coordinate through either pure hierarchy or pure market exchange, especially when complementarities are non-generic and require alignment between actors (Adner, 2017; Jacobides et al., 2018).

In this thesis, a platform-based ecosystem is not understood narrowly as a digital application, but as a value system in which a focal actor coordinates complementors and customers through shared interfaces, standards, governance rules, and technological or digital architectures. This understanding is consistent with platform and ecosystem literature, where platforms are seen as structures that enable complementary innovation and operations around a common architecture (Cusumano et al., 2019; Gawer & Cusumano, 2014). In the DH context, this could involve coordination of heat and cooling supply, thermal storage, customer-side heat pumps for customisation, demand flexibility, data flows, predictive maintenance, anomaly detection, and optimisation services. The platform logic therefore differs from the traditional DH model, where the DH firm mainly controls production and distribution to customers, within a hierarchy-based value system.

However, it is important not to overstate the extent to which DH firms already operate as platform-based ecosystems. Many DH firms have long relied on external suppliers, installers, consultants, maintenance firms, and equipment providers. These relationships may involve complementarity, but they often remain passive extensions of the incumbent hierarchy-based value system. They become more platform-like only when external actors are actively coordinated around shared interfaces, data flows, modular architectures, and complementary innovation. In such cases, the DH firm, or another focal actor, does not merely purchase inputs from suppliers, but orchestrates a broader configuration of actors that jointly contribute to customer value. This distinction is important because ecosystems are not only collections of collaborating firms; they involve structured interdependence between actors whose contributions must be aligned for value to be created (Adner, 2006, 2017; Ganco et al., 2020). There are indications of active ecosystem formation in the cases, see Paper IV, but this should be distinguished from the more generic ecosystems that already surround many DH firms. DH firms commonly interact with complementors that provide installation, automation, and maintenance services for heating systems in buildings. However, these generic ecosystems are often weakly coordinated, locally embedded, and difficult to scale

or replicate across DH networks. By contrast, digital platforms and front-end heat pump configurations, including 5GDHC (Abugabbara, Javed, & Johansson, 2022; Lindhe et al., 2022), may create more active forms of coordination as platform elements. Front-end heat pumps can provide local customisation at the building level, thereby making DH solutions less configurational and less dependent on case-specific engineering for each building (Wesche et al., 2019). In this sense, platform-based coordination may compensate for variation across customer buildings by enabling more standardised modules, interfaces, and control functions. This, in turn, may support scaling across many customers and replication across different DH systems.

This platform logic also connects to the role of variation and diversity in innovation. Research on radical exploration emphasises that heterogeneous knowledge inputs and cross-sector interaction expand the space of possible innovations (Laursen, 2012; Laursen & Salter, 2014). Similarly, ecosystem research highlights how focal firms and complementors create value through differentiated but interdependent contributions (Helfat & Raubitschek, 2018; Jacobides et al., 2024). This builds on evolutionary innovation theory, where diversity in technological and organisational routines is a source of variation and renewal (Dosi, 1982; Nelson & Winter, 1982). For DH firms, such diversity may arise upstream through suppliers and surplus heat providers, downstream through customers and property owners, and horizontally through other city utility sectors[11]. Platform-based ecosystems may therefore support radical exploration by bringing heterogeneous capabilities into a more coordinated innovation process.

Digitalisation is central to this shift because it makes distributed resources visible, measurable, and actionable across organisational boundaries. AI and Machine learning, sensors, IoT, automation, and predictive analytics can support forecasting, optimisation, anomaly detection, predictive maintenance, demand-side management, and customer segmentation. Paper II illustrates this potential by showing how machine learning may enable more advanced forms of system optimisation and operational decision-making in DH. However, such applications typically require data and capabilities distributed across several actors, including DH operators, software firms, sensor suppliers, control system providers, property owners, customers, and researchers. Digitalisation therefore does not only improve internal efficiency; it may also create new interfaces through which complementors and customers become more integrated into innovation processes.

A platform-based DH ecosystem may create value by connecting several sides of the market. One customer may need cooling and return surplus heat, while another

[11] Diversity operates at multiple levels: at the micro-level, firms benefit from heterogeneous capabilities and search behaviours, while at the macro-level, cities generate innovation by concentrating diverse people, skills, and industries, thereby creating dense environments for knowledge exchange (Jacobs, 2016). Book by Jane Jacobs, from 1969.

customer may need heating. A building-level heat pump may provide customised heating, cooling, flexibility, or recovered heat depending on system conditions. Surplus heat providers, property owners, digital service firms, technology suppliers, and DH operators may jointly contribute to system optimisation. In such configurations, value is created not only by delivering heat through a pipe network, but by coordinating flows of heat, cooling, data, flexibility, and services across a wider actor constellation. This points toward a more multi-sided understanding of DH value creation, where network effects may arise as additional customers, complementors, data sources, or flexible assets increase the value of the system for other participants (Hagiu & Wright, 2015; McIntyre et al., 2021).

The platform logic also introduces new strategic dynamics. Platform-based ecosystems may involve multihoming, where customers or complementors participate in more than one system, and platform envelopment, where one platform absorbs or replaces functions previously controlled by another actor (Eisenmann et al., 2011; Jia et al., 2019). These dynamics create opportunities for scaling and innovation, but they also raise questions about control, dependency, openness, and value capture. The relationship between platform owners and complementors may be collaborative, but it may also become competitive when actors' roles change over time (Adner & Lieberman, 2021). These governance trade-offs are discussed further in the following section.

The empirical findings of this thesis indicate that platform-based ecosystems should be understood as an emerging rather than completed transformation in the DH sector. Paper III shows how external search may shift relationships from supplier-based arrangements toward more complementor-like roles when innovation depends on distributed capabilities. Paper IV further illustrates how DH innovation pathways may move from isolated firm-level initiatives toward more platform-oriented configurations. However, fully developed platform-based ecosystems remain limited. The significance of the platform concept is therefore not that DH firms have already transformed into platform firms, but that it helps explain how radical exploration may be organised when innovation depends on customer-side assets, digital technologies, complementors, and new forms of multi-sided value creation. In this sense, platform-based ecosystems represent a possible coordination logic for the next phase of DH transformation.

5.3.3 Governance trade-offs and new risks

The findings caution against viewing platform ecosystems as a frictionless solution. Platforms introduce new governance challenges, including issues of control, dependency, and competition between platform owners and complementors (Adner & Feiler, 2019; Adner & Lieberman, 2021; Panico & Cennamo, 2022). While network effects can increase value for participants (Jia et

al., 2019), they can also lead to temporary monopolies and lock-in (McIntyre et al., 2021), raising concerns about long-term customer choice and the need for regulatory oversight (Cennamo et al., 2025).

The role of municipalities emerges as particularly important in this context. In several cases, municipal ownership or coordination enabled risk-taking, long-term investment, and cross-utility collaboration, consistent with earlier findings on urban infrastructure governance (Denis & Florentin, 2024; Florentin, 2019). However, reliance on local public actors also raises questions about scalability and transferability to contexts with different institutional arrangements. European countries also use different ownership and governance models to balance public control, operational efficiency, and scalability. In the UK and France, for example, concession-based models allow municipalities to retain ownership of infrastructure assets while outsourcing operation and maintenance through long-term contracts to large energy-service firms. Mixed ownership may provide another way to combine public oversight with private-sector capabilities. These governance issues are important because platform-based ecosystems depend on diverse actors and distributed capabilities. The same openness that supports innovation may also increase coordination problems, dependency, and value-capture tensions. For DH firms, the challenge is therefore not only to involve more complementors, customers, and infrastructure actors, but also to govern their interdependencies in ways that preserve system reliability, customer choice, and long-term public value.

6. Conclusions

This section concludes the thesis by synthesising the main findings and considering their broader theoretical and practical implications. The thesis addressed two research questions. Regarding RQ1, the findings show that innovation in the DH sector under conditions of energy transition remains predominantly incremental, exploitation-oriented, and strongly shaped by path dependence. Transformation is gradual and uneven, with innovation concentrated around established technologies, suppliers, and hierarchy-based value systems, although increasing technological and market uncertainty is creating pressure for broader exploration. Regarding RQ2, the findings show that DH firms engage in exploration with external partners by extending search beyond established technological and organisational boundaries. The five identified patterns demonstrate that such exploration differs in technological distance, actor constellations, leadership, and governance. As exploration moves further from the incumbent firm's core, suppliers, customers, entrants, and complementors assume greater roles, and value creation may shift from hierarchy-based arrangements towards ecosystem-based configurations or, alternatively, market-based substitution and disruption.

Taken together, the findings show that transformation in district heating is characterised by a tension between continuity and reconfiguration. Exploitation, incremental innovation, and hierarchy-based value systems remain dominant, reflecting long-lived infrastructure, accumulated capabilities, established supplier relationships, and strong requirements for operational reliability. At the same time, increasing technological and market uncertainty creates situations in which these established search processes are insufficient, and firms are starting to explore beyond familiar technologies and organisational boundaries.

The overall conclusion is that transformation in DH is not primarily a linear technological shift from one generation of technology to another. Rather, it is a gradual reconfiguration of how innovation is searched for, how actors collaborate, and how value creation is organised across firms. Radical exploration appears selectively in innovation initiatives where external knowledge and complementary capabilities are required. As exploration moves further from the incumbent firm's technological and organisational core, customers, entrants, complementors, and other actors become more important, and the governance of innovation becomes increasingly distributed and complex.

The remainder of this chapter develops the implications of this synthesis. Section 6.1 summarises the overall innovation dynamics identified in the thesis, Section 6.2 presents the theoretical contributions, Section 6.3 discusses practical and policy implications, and Section 6.4 addresses limitations and directions for future research.

6.1 Innovation dynamics in DH firms

The findings reveal a sector in which the dominant innovation logic remains exploitation-oriented, while more exploratory forms of innovation emerge selectively at the boundaries of established systems. DH firms have developed strong capabilities for improving production, distribution, and operational efficiency within existing technological and organisational architectures. These capabilities have supported substantial adaptation over time, but they also reinforce path dependence (Dosi, 1982) and concentrate search around familiar technologies, established suppliers, and accumulated experience. Such backward-looking and experiential search is effective under relatively stable conditions (Gavetti & Levinthal, 2000; Levitt & March, 1988), but may restrict the ability to identify more distant alternatives. Fragmentation across many relatively small and locally embedded DH firms further reinforces local search and limits the development, diffusion, and scaling of capabilities for radical exploration. This is consistent with the broader finding that DH innovation has historically concentrated on incremental efficiency improvement and system optimisation rather than more transformative change (Sernhed et al., 2018).

The empirical cases show that more radical exploration emerges when problems cannot be addressed through such local search alone. In these situations, innovation increasingly depends on knowledge, technologies, and resources located outside the focal DH firm. Radical exploration therefore involves crossing both technological and organisational boundaries (Rosenkopf & Nerkar, 2001).

The empirical cases reveal five patterns of radical exploration, illustrating different ways in which external search can be organised. The first pattern involves new-to-the-world product innovation, where DH firms facing technical problems that cannot be solved internally engage specialised technology suppliers to search for distant solutions. Exploration is effectively outsourced, while the incumbent hierarchy-based value system remains largely unchanged. The second pattern concerns production- and city-oriented innovation, where DH firms search for synergies with other utilities and industries, for example through waste heat recovery, cooling, or carbon capture. Here, innovation mainly recombines established technologies and builds on existing municipal and supplier relationships, recently defined as industrial ecosystems (Burström et al., 2024). The third pattern extends exploration both upstream toward external heat providers

and downstream toward customers. Customer integration, digitalisation, and new forms of heat and cooling exchange broaden the solution landscape, although the DH firm generally retains its position within the existing value system. The fourth pattern is characterised by entrant-led innovation, where new actors combine existing technologies such as heat pumps and thermal networks into new system configurations and business models that may disrupt and replace incumbent heating or cooling systems. Finally, the fifth pattern involves emerging ecosystem-based configurations in which property owners, DH firms, technology suppliers, municipalities, and other actors jointly combine complementary resources. In these cases, innovation becomes more distributed and governance shifts from hierarchical control toward coordination among interdependent actors. The five patterns should not be understood as sequential stages through which DH firms progress, but as alternative manifestations of radical exploration under different technological, organisational, and institutional conditions. Despite these differences, a broader direction can nevertheless be observed across the patterns. The locus of innovation tends to move from the production core of the incumbent DH firm toward organisational and value-system boundaries. At the same time, leadership of innovation becomes increasingly distributed. Suppliers, customers, property owners, entrants, and ecosystem focal actors may take more important roles in identifying problems, developing solutions, and coordinating complementary resources. This is consistent with ecosystem perspectives in which value creation depends on interdependent contributions from multiple actors rather than on the activities of a single focal firm (Adner, 2017; Jacobides et al., 2018, 2024). Radical exploration is therefore not only a matter of searching for distant technologies; it also involves searching for suitable partners and forms of inter-firm coordination. The empirical patterns show that, as innovation moves outward from the incumbent core, both the actor leading exploration and the governance arrangements surrounding innovation may change.

This leads to a broader conclusion regarding transformation in the heating sector. Competition and innovation increasingly concern alternative configurations of value creation rather than individual technologies alone. The traditional hierarchy-based DH system may be extended by incorporating new technologies and partners; ecosystem-based configurations may emerge where complementary resources need to be coordinated across independent actors; or more decentralised market-based alternatives may substitute functions previously performed by the incumbent DH system. These configurations may coexist and compete rather than develop along a single transition pathway. This interpretation builds on the distinction between hierarchy-, market-, and ecosystem-based value systems (Jacobides et al., 2018, 2024) and on the finding that new resources and entrepreneurial action can alter relationships between incumbents, entrants, complementors, and customers.

Platform-based ecosystems represent one possible coordination mechanism within this development, particularly where digital technologies, customer-side assets, heat pumps, storage, cooling, data, and flexibility need to be combined across organisational boundaries. Platform and ecosystem research emphasises that such configurations depend on complementarities, interdependence, and coordination across actors (Adner, 2017; Cusumano et al., 2019; Jacobides et al., 2018). However, the findings do not indicate that DH has already undergone a general shift toward platform-based organisation. Such configurations remain emerging and introduce new governance challenges involving control, dependency, value capture, system reliability, and customer choice.

The overall transformation of DH is therefore best understood as selective and configurational rather than as a linear technological transition. Established infrastructure and exploitation remain important, but their boundaries are increasingly challenged by radical exploration and distributed innovation. The long-term development of the sector will depend not only on which technologies become available, but also on which actors are able to combine them, how their interdependencies are governed, and which value-system configurations are able to create and capture value under changing conditions.

6.2 Theoretical contributions

This thesis contributes to innovation research, DH research, and the energy-transition literature by showing how transformation in a mature infrastructure-based industry can be understood through the interplay between radical exploration, external search and collaboration, value system configurations, and supporting concepts such as digitalisation, product-service systems, ecosystems and platform-based ecosystems.

The main theoretical contribution is to show that transformation in incumbent infrastructure-based industries is not only a technological transition, but also a reconfiguration of search processes, actor roles, and value system architectures. This contribution is developed through four related theoretical contributions.

First, the thesis extends research on exploration and search theory by applying it to large-scale infrastructure industries. The findings show that radical exploration in DH does not necessarily imply a complete break with existing hierarchical structures. Rather, DH firms often combine continued exploitation of established assets with selective, problem-driven exploration across technological and organisational boundaries. This nuances the exploitation - exploration dichotomy (Lavie, 2006; Lavie et al., 2010; March, 1991) and connects to research on ambidexterity and paradox theory (Albert, Kreutzer, & Lechner, 2015; Laursen & Salter, 2014; Rothaermel & Alexandre, 2009; W. K. Smith & Lewis, 2011; Tóth

et al., 2022; Xing et al., 2024). The contribution is to show that, in mature infrastructure sectors, exploration may be organised not as an internal strategic shift alone, but through selective boundary spanning, externalised innovation activities, collaboration with complementary actors, and, in some cases, disruptive entry by new actors when incumbents remain inert.

Second, the thesis contributes to research on innovation search and inter-firm collaboration by showing how external search expands the solution landscape available to DH firms. The findings indicate that individual DH firms, when acting alone, tend to remain confined to a limited and locally familiar solution landscape. By engaging with suppliers, customers, heat producers, digital actors, and other external partners, firms gain access to complementary knowledge and more distant technological alternatives. This contributes to search theory by illustrating how complex and partly non-decomposable transition problems require collaborative search rather than isolated problem solving. It also contributes to the governance literature by showing that the organisation of collaboration matters: innovation outcomes depend not only on openness, but also on how roles, responsibilities, incentives, dependencies, and knowledge integration are structured across actors (Adner, 2017; Nickerson & Zenger, 2004; Rosenkopf & Nerkar, 2001).

Third, the thesis advances value system theory by showing how transformation in heating can be understood as shaped by competition and coordination between different value system configurations. The findings show that competition increasingly occurs not only between individual technologies, but between hierarchy-based gas and DH systems, market-based solutions such as individual heat pumps, and emerging ecosystems and platform-based ecosystems. These configurations represent different organisational logics, each with distinct implications for innovation, coordination, value creation, and value capture. By applying the value system perspective (Jacobides et al., 2018, 2024), the thesis shows that radical exploration is conditioned by the structure of the value system in which firms are embedded. Hierarchy-based systems support reliability and control but may constrain external search, while ecosystem and platform-based configurations can expand the search space by coordinating heterogeneous actors, technologies, and user needs. This also suggests that solutions capable of scaling across contexts may need to become more generic, and replicable than traditional DH solutions, which are often highly local and context dependent.

Fourth, the thesis contributes to platform and ecosystem literature by showing how ecosystem and platform-like coordination mechanisms may emerge in asset-intensive and regulated sectors. In this context, platforms are not primarily digital marketplaces. Rather, they are socio-technical arrangements that coordinate interdependent infrastructures, customer-side technologies, data flows, and new service offerings. Digitalisation, AI, product-service systems, customer integration, and 5GDHC can therefore be understood as supporting concepts that enable new forms of coordination around physical infrastructure. The thesis

thereby extends the application of platform and ecosystem perspectives to a sector characterised by long investment cycles, strong regulation, local embeddedness, and infrastructural path dependence. Taken together, these contributions shift attention from technological pathways alone to the organisational and inter-organisational processes through which transformation unfolds. The thesis shows that slow transition in DH is not merely a matter of technology diffusion, but also a coordination problem rooted in existing value-system architectures, institutional arrangements, and incumbent routines. By linking innovation search, inter-firm collaboration, and value-system configuration, the thesis provides a framework for understanding how radical exploration may contribute to transformation in mature infrastructure-based industries. In this perspective, transformation depends not only on the availability of new technologies, but also on how firms access external knowledge, organise collaboration across organisational boundaries, and coordinate complementary resources within changing value systems.

6.3 Practical and policy implications

From a practical perspective, the findings suggest that DH firms may benefit from complementing their traditional production-oriented focus and reliance on favourable public policies with more systematic engagement in external collaboration and customer integration. Digital technologies and electrification appear to play an important enabling role, but organisational capabilities and governance arrangements are equally important, for instance developing capabilities for ecosystem participation and platform governance (Cusumano et al., 2019; Gawer & Cusumano, 2014).

From a public policy perspective, the thesis highlights a tension between regulation that ensures stability and regulation that enables innovation. While public funding and protection remain important, an overly strong reliance on subsidies and price regulation risks reinforcing incumbent trajectories, delaying necessary experimentation, and increasing the risk that DH systems are disrupted by electrification and heat pumps. Policies that support platform development, interoperability, and collaborative experimentation may more effectively address the complexity of the heating transition than technology-specific incentives alone.

Another public-interest dilemma concerns who represents the interests of the city-level energy system when no DH operator exists or when its coordinating role is weak. In parts of Western Europe, where heating is still dominated by natural gas and DH is limited or absent, an emerging pathway is for building owners - both households and apartment buildings - to install air-to-air heat pumps (in a market-based value system). These relatively inexpensive components provide space heating during much of the winter and comfort cooling in summer, while the incumbent gas connection is retained for peak heating and domestic hot water.

Although this hybrid solution may substantially reduce gas consumption and be economically attractive for individual building owners, widespread adoption can increase peak electricity demand and create constraints in electricity generation and distribution. It may also create a new form of path dependence, making later conversion to DH or more integrated and sustainable heat pump solutions more difficult. From a platform perspective, this can be interpreted as a form of multihoming, in which customers remain connected to both the gas and electricity systems. Such a configuration, emerging through largely market-based individual decisions, may be rational at the building level while being suboptimal from a city-system perspective, because investment decisions are made independently without an actor responsible for coordinating the long-term configuration of the urban heating system. Where a focal platform owner exists, it could instead pursue an envelopment strategy, combining a solution such as DH with decentralised heat-pump network solutions (5GDHC) within a broader integrated energy offering.

6.4 Limitations and future research

This thesis explores how DH firms engage in radical exploration through external collaboration in the context of the energy transition. While the findings provide valuable insights, several limitations should be acknowledged.

The study adopts the analytical distinction between exploitation and exploration, which, although useful, simplifies the complexity of organisational practices where both modes often coexist, as ambidexterity – a paradox. The empirical focus on relatively innovative firms further limits generalisability, as more conservative actors are underrepresented. Additionally, radical exploration is operationalised as technological and organisational boundary spanning. While consistent with the theoretical framework, this definition may not capture institutional or political and policy dimensions of radical change. While these dimensions are acknowledged as most plausible rival explanations, they fall outside the primary analytical focus of this study.

The analysis of collaboration is conducted mainly from the perspective of the focal firm, which constrains insights into power dynamics, value capture, and unsuccessful partnerships. Moreover, the observed shift towards ecosystem-based value creation should not be interpreted as linear, as hybrid arrangements remain prevalent.

Methodologically, the qualitative and context-specific design enables in-depth understanding but limits broader generalisability and transferability. Although measures such as triangulation were employed, the regional focus and the researcher's background may have influenced interpretation.

Future research could address these limitations by including a wider range of firms and applying quantitative or mixed methods to enhance generalisability. Several questions remain open. For example, how do ownership structures (public versus private) and price regulation influence innovation, improvement, and scalability? Comparative studies across infrastructure sectors undergoing similar transitions could further test the applicability and transferability of the findings. Further studies may also examine more direct measures of system complexity and explore ecosystem governance from multiple actor perspectives.

Taken together, these insights contribute to a deeper understanding of how incumbent infrastructure-based firms can navigate complex transitions through innovation, collaboration, and evolving value system configurations - beginning to move from silos toward ecosystems.

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