

Review

Is Innovation Redesigning District Heating? A Systematic Literature Review

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Abstract: The district heating (DH) industry has been characterized by continuous innovation for several decades, but there is limited knowledge on the characteristics of the sector's innovation activities, arguably the most important information for understanding how the sector can continue to develop and further support the energy transition of society. We perform a systematic literature review (SLR) to identify the types of innovation, the levels of innovation and the relation between different innovations in the DH sector. A total of 899 articles are analyzed and coded into eight groups: fuel, supply, distribution, transfer, DH system, city system, impact and business. Most of the articles (68%) were identified in the groups: "supply", "DH system," and "impact", with a focus on DH from a system or production perspective and its environmental impact. We find that there is limited research on DH firms' challenges, including management perspectives, such as asset management and customer focus. Despite this potential, we find only a limited number of articles related to innovation. Not much scholarly attention has been given to areas of large cost-saving, especially capital cost.

Keywords: district heating; literature review; innovation



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1. Introduction

1.1. District Heating

Approximately half of the energy consumed in Europe is used for heating and cooling [1]. District heating and cooling (DHC) is a key technology for increasing the efficiency of heating and cooling processes and has been acknowledged by the European Commission as an important instrument to decarbonize energy usage [2]. DHC is an important part of the "clean energy" initiative (outlined in the "European Green Deal") [3].

DH is a system in which heat is collected from a variety of heat sources and distributed to customers by means of a hydraulic system [4]. The important assets of a DH system (DHS) are the "heat distribution network" (HDN) and the "heat transfer units" (HTU) at the customer side. A DHS can have a variety of heat supply units. Fuel can be used to produce hot water, but heat can also be captured from other non-fuel-based sources, such as geothermal, solar and from surplus heat [4].

Several large cities in Europe and the US introduced a first-generation DH (1GDH) steam-based system around the turn of the nineteenth to the twentieth century. Some of these systems are still in operation. In Europe, DH expanded rapidly after the Second World War, in the 1950s and 1960s. New systems such as second-generation DH (2GDH) are based on hot water distribution that uses steel pipes in hollow concrete ducts for distribution. A major proportion of these pipe ducts are still in operation, usually in city centers [5].

Early drivers for DH expansion were to improve electric power generation and to reduce dispatch of hot condensing water from power generation [6], which also improved local air quality. The 1973 oil crisis triggered decades of DH expansion and led to a change in fuel supply in many countries (from fossil to biofuels) [7]. Biomass, natural gas and coal replaced imported oil across Europe. The Nordic countries were early to introduce a

ban on waste landfills, generating heat recovery from the incineration of domestic waste. Gradually, a new type of DH pipe was developed and introduced, labeled third-generation DH (3GDH). The 3GDH pipes were pre-insulated, prefabricated and buried directly into the soil. In parallel, more standardized, compact, controllable and prefabricated HTUs at the customer side were developed and increased control systems for leakages were established.

Around the turn of the millennium, global warming and the need to reduce greenhouse gases (GHG) became a high priority. DH countries that had converted early from oil to biomass were ahead, yielding low emissions from their DH systems. Other countries were locked into inferior solutions. For example, both the UK and the Netherlands proceeded with separate heating, and electrical power sectors post WWII [8]. Heating was provided from individual boilers in each building, often supplied by natural gas from national grids. Electrical power was supplied from inefficient condensing power plants, where the waste heat was not reused in DHNs. Consequently, DH's market share is low (2–5%) in some countries compared to more than 50% in Denmark and Sweden [9]. The third category of countries is in Eastern Europe. They have a high market share of DH but have DH and condensing electrical power generation based mainly on fossil fuels [10].

As a result of shifts from fossil fuel to other heat sources, the industry has significantly contributed to lowering greenhouse gas emissions. In response to the 2050 targets of fossil-free societies, increasing attention has been given to existing low-temperature heat sources. The usage of low tempered heat sources coming from urban contexts like infrastructure (metro systems, sewage water) and service sector buildings (like hospitals, offices) and data centers are often referred to as fourth-generation DH (4GDH). From a technical standpoint, 4GDH represents a modest reduction of system temperatures and no significant change in the components or system architecture.

There are many advantages with lower distribution temperatures in DHNs, including decreased heat losses and increased lifetimes of the pipes. The main advantage is that more sources of surplus heat can be used, allowing for the establishment of a circular economy where a city can harvest its own heat.

Most of the world's large and existing DH networks were constructed under public ownership, but today the ownership is more heterogeneous. Policies, such as regulation, taxes and subsidies, have traditionally been crucial for the DH expansion. Today, some countries protect their DH operators, while others have deregulated and even privatized the industry, exposing DH technology to competition from alternative heating sources.

1.2. Innovation Theory

Innovation is a key mechanism for improving the performance of technologies. There are different definitions of innovation, but we have chosen to follow the definition from the Oslo Manual [11]. It states that an innovation is a new or improved product, or process (or a combination thereof) that differs significantly from the unit's previous products or processes and that has been made available to potential users (products) or brought into use by the unit (process).

The Oslo Manual differentiates between innovation at different levels, including: (i) the component/product/service at the departmental level, within a firm or an organization, (ii) the system/process at the firm or organizational level and (iii) the cross-sector system at the inter-organizational level.

The DH industry is categorized as a “scale-intensive industry” [12] because it requires a high market share within its coverage, and it can be seen as an infrastructure-based service operated either by municipal or private stakeholders. The heat production and distribution are performed in a central unit, and each DHS involves a large amount of engineering in the modeling, planning, construction and operation phases, necessitating the input from a number of suppliers (heat providers, engineers, pipe providers, pump providers, heat transfer unit providers and others).

From an innovation perspective, the DH industry can be categorized as a “supplier-dominated industry” as product innovations are diffused from the technology suppliers

to the DHS operators. Diffusion is defined as part of a successful innovation process and includes development, implementation and adoption of an innovation (made by other firms) to another company [13].

Another dimension is whether the novelty of the innovation is incremental or radical [13]. Examples of the type of innovation are shown in Figure 1. At the component level, improved detection of water leakage or faulty heat transfer units are examples of incremental innovation. A radical innovation would be monitoring to predict corrosion on pipes. In between the radical and incremental innovation is the “new to the enterprise” (a specific DH operator) type of innovation, which can be exemplified by the new automation (digitalization) of valves and heat transfer units.

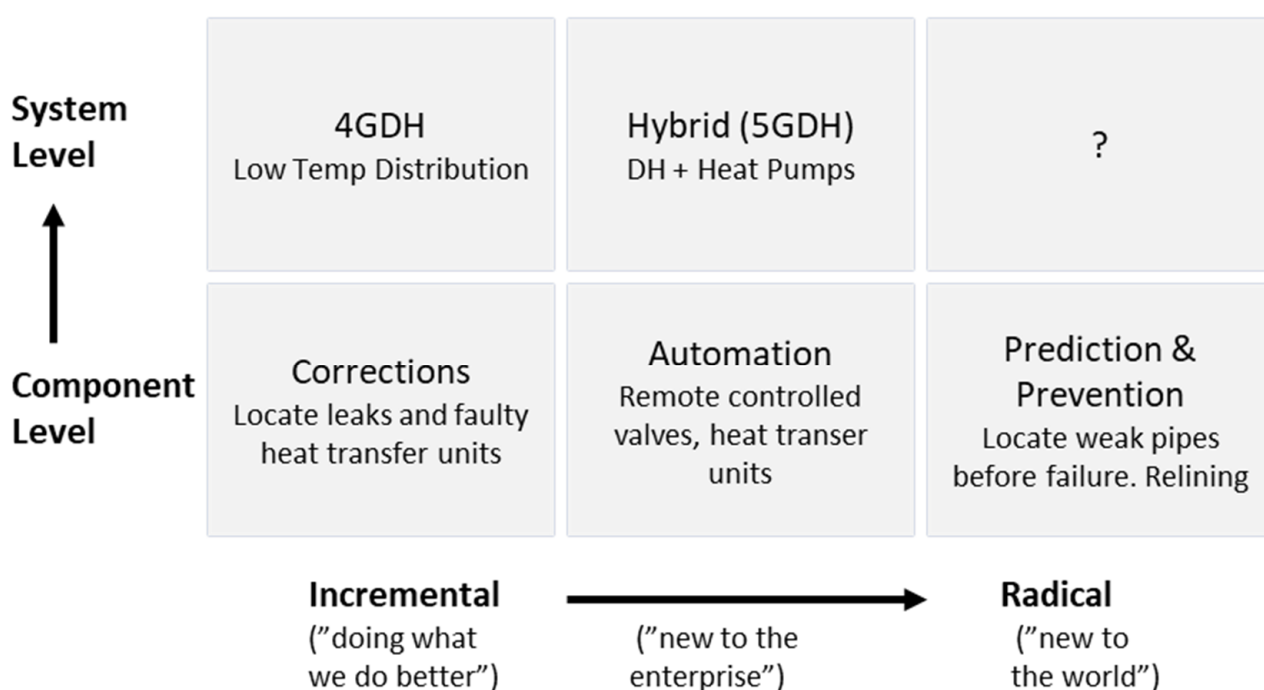


Figure 1. The different dimensions of innovation that are applied to the distribution of district heating (DH), based on [14]. Examples of innovation in the DH sector. On the lower level is the component type of innovation, from left incremental innovation to radical innovations. On the upper level is the system type of innovation. In the upper right corner is a question mark. It can be disputed what is radical innovation at the system level.

At the system level, an example of incremental innovation is the reduction of system temperatures, which implies a transformation to 4GDH. An example of a new to enterprise innovation may be the combination of DH with demand-side heat pumps (installed in customer buildings), which is a hybrid system that some class as a 5GDH (ultra-low-temperature system). An example of radical innovation at the system level could involve the combination of 4GDH, 5GDH and distributed heat storages and combined with comfort cooling at customer sites, but these developments are in early stages and are currently poorly understood.

We return to the research question: What characterizes innovation in the DH sector?

The purpose of the article is to better understand how academic research is contributing to innovation and what trends and patterns that can be distinguished. The district energy sector has a significant potential to contribute to the ongoing energy transition. It is an industry that has been around for more than a century, successfully adapting its activity to changing circumstances. It is important to understand how the sector has successfully innovated in the past both to share knowledge on efficient capabilities to adapt but also to understand how the sector can remain competitive given the challenges it is facing today and reaching 2050 goals [15].

2. Methods

2.1. Method of Analysis

A systematic literature review following the methodology outlined in [16] is applied to summarize and synthesize the prior research. Such reviews are used to compare and analyze empirical findings, models and explanations. To understand innovation in DH, we focus on the core processes that are heat-distribution and transfer. There is a risk of limiting the findings by focusing only on these areas; thus, other aspects, including fuel, heat supply and impact/output of DH (e.g., the DH value chain), were investigated.

We used the “Scopus” database as it extensively covers both the refereed journals and conferences where DH information is featured. More than 19,000 publications appear for the search term “district heating”. As a second source of information, we used “Ei Compendex” on “Engineering Village”. We focused on peer-reviewed journal publications and new conference papers. The selection means that there are publications that we do not capture, for instance, reports from national technical programs in China, Germany and Sweden and reports related to specific European programs. To avoid bias, the search was not broadened beyond peer-reviewed publications.

The derived search string was based on an exploratory literature review to identify the key concepts and core papers. Different search strings were tested iteratively. To ensure extensive coverage, five searches were performed, where the findings were combined, and duplicates were removed.

2.2. Data Collection

The five searches are outlined below:

Search one: To find the most influential papers, we used citations as a proxy. We identified the 100 most-cited publications (2000–2020) by searching Scopus with the term “district heating”;

Search two: To find recent papers that are too new to have many citations, we used all publications with 10 or more citations in Scopus with the search string “district heating” (2018–2020);

Search three: To develop the search and identify journals addressing innovation in district energy, the search string “district heating” and either “innovation”, “development”, “business,” or “improvement” was used (2014–2020) in Scopus;

Search four: The search string from search three was cross-tested by being applied to the Ei Compendex database. The 100 most-important publications regarding innovation in DH were selected by applying the database’s “RELEVANCE” criteria (2014–2020);

Search five: The search string from search three was applied to another database (Ei Compendex) to include conference papers and papers that were under review (2018–2020).

2.3. Data Analysis

To identify which publications are innovation-related from a technological, business or social perspective, a first coding was applied to the identified dataset in the five searches above. The analysis encompassed titles, keywords and abstracts. If the relevance of the content was unclear, the papers were read. The analysis sorted the papers in four ways. First, we removed irrelevant papers. Second, we identified impact studies that did not focus on the nature of DH but more on its output, such as its impact (usually beneficial), especially in terms of their energy savings or emissions. Third, we differentiated the articles from business and the social sciences from those from the technological/engineering sciences. Fourth, given the broad scope of technologically-orientated publications, those were further sorted into six categories following the conventional DH value chain [4], as illustrated in Figure 2. The steps of the chain reflect (1) fuel, (2) supply of heat, (3) distribution of heat and (4) transfer of heat. Coding reflects the value chain steps 1–4. In addition, three additional groups of literature were identified: (5) DH system; (6) integrated city systems that involve all city utility infrastructure system perspectives, including DH; and (7) impact/benefits of DH. Finally, group (8) represents DH in the context of business and social science. The

links between the literature categories are shown below. The impact/benefit of DH (7) and business/social science papers (8) are not mapped in the figure as they address the system as a whole.

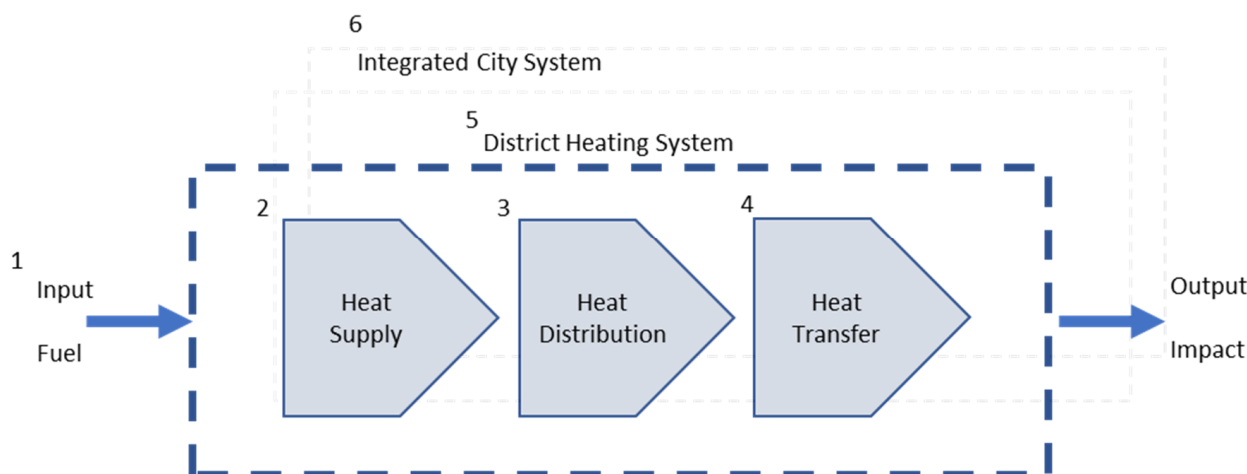


Figure 2. The value chain of DH adapted and interpreted from [4]: (1) fuel, (2) supply, (3) distribution and (4) transfer. All together, they make up the DH system (5), which is a part of integrated city systems (6).

All relevant articles were coded to one group only, and all groups were made mutually exclusive.

Each group was analyzed according to the frequency of keywords. The keywords were used as a proxy to identify clusters (themes of similar keywords), approximately 100 keywords were analyzed per group.

Articles from two groups, distribution and transfer, were scrutinized further as these activities are at the core of DH activity and, as a result of the many decades of DH operation, should contain innovative actions. The papers in the two groups were coded in terms of different stages of innovation “phase” (P) and unit of analysis (component, product or service) referred to as “level” (L), see Figure 3.

LEVEL	PHASE	
	P1	P2
	INSIGHT, PROBLEM & POTENTIAL	INVENTION & INNOVATION
INTERORGANISATIONAL RELATIONS L3	Gaining insight and knowledge at interorganisational level	Contributing to inventions and innovations at interorganisational level
PROCESS & SYSTEM L2	Gaining insight and knowledge at process or system level	Contributing to inventions and innovations at process or system level
PRODUCT & SERVICE L1	Gaining insight and knowledge at product/service level	Contributing to inventions and innovations at product/service level

Figure 3. Coding groups by “phase” (P1 and P2) and by “level” (L1, L2, L3).

Phase refers to different stages of innovation, where an idea may be input into a development process and ends with a commercialized innovation. Phases were divided into P1 (insight, problem and potential) and P2 (invention and innovation process). P1 articles gave insight into and identification of a problem, an opportunity, a knowledge gap,

a future direction, a development potential or an idea. The purpose of an article may be to identify a future direction, funding needs, changed policy instrument needs or knowledge progression. A purpose can also be to verify something, as a part of a feasibility study or similar.

P2 articles included ideas and inventions that could be a step towards innovation. Innovation is triggering substantial efforts in research and development.

L1 includes the component, product or service level for technical publications or the firm or department level for management-oriented papers.

L2 is the system level, such as the DH system level, but also refers to the supply, distribution and transfer subsystem levels, including multiple modules/components. For management publications, it refers to the firm level.

L3 consists of intraorganizational relations, involving multiple actors, with the interaction between independent systems, which are external to DH.

Articles that were traced to innovation in the groups (heat) distribution and transfer were coded in two additional dimensions. Articles coded in the distribution group were coded as existing networks or new networks, vs. value to profit and loss statement (operating expenditures) or balance sheet (capital expenditures).

Articles in the transfer group were coded as existing systems or new systems, vs. value to the DH system (production) or to the customer.

3. Results

A total of 998 articles were collected from the databases, which were subsequently reduced to 899 after elimination of duplicates or articles identified to be irrelevant (29 articles).

Five searches were made, and the articles were grouped into one of eight segments, called fuel, supply, distribution, transfer, DH system, city system, impact and business. Figure 4 shows the relative importance of the five searches per group.

3.1. Group 1: Fuel

Fuel is the traditional type of energy used for DH supply. Fuel includes fossil fuels, coal, oil and gas, but renewables have become increasingly important in recent decades, such as biomass (solid, liquid and gas). Another fuel that is still growing in demand is combustible waste fractions. Recently, hydrogen that is produced from excess electric energy has started to be used.

Fuel contains 48 articles (5% of all), which makes it the second smallest group, where only the distribution group has fewer articles. It had its highest relative score in search 1, which involved the most cited articles since the year 2000 (search 1).

The ten most frequent keywords are listed in Figure 5.

Further analysis was performed by grouping the keywords, which lead to the following areas: biomass (forestry), biomass (agro), biogas and waste.

The most cited articles per theme are [17] for biomass, [18] for solid waste, [19] for sludge waste and recovery of nutrients, and [20] for biogas.

Fewer hits were obtained when a search was performed on newer articles, which implies that the field has matured and that newer fuel sources are well understood. Another reason may be that there is less need for fuel because of the emergence of low-temperature heat sources (4GDH) and an increased interest in using surplus heat. A third reason may be there is an increased demand for using biomass for other purposes, such as vehicle fuel or as industrial input. Waste as fuel is disputed due to the high content of fossil fuels, and the societal ambition to increase the share of recycling of plastic material is increasing.

3.2. Group 2: Heat Supply

Heat supply refers to plants that produce hot water. Traditionally this heat comes from the incineration of fuels, but more recently, other heat sources were used, such as surplus heat, solar and geothermal heating.

This is the largest group (315 articles), consisting of 35% of all articles. 48% were conference papers that were published from 2018 to 2020 (search 5), and 21% dealt with “optimization and demand forecasting”.

The ten most common keywords are listed in Figure 6.

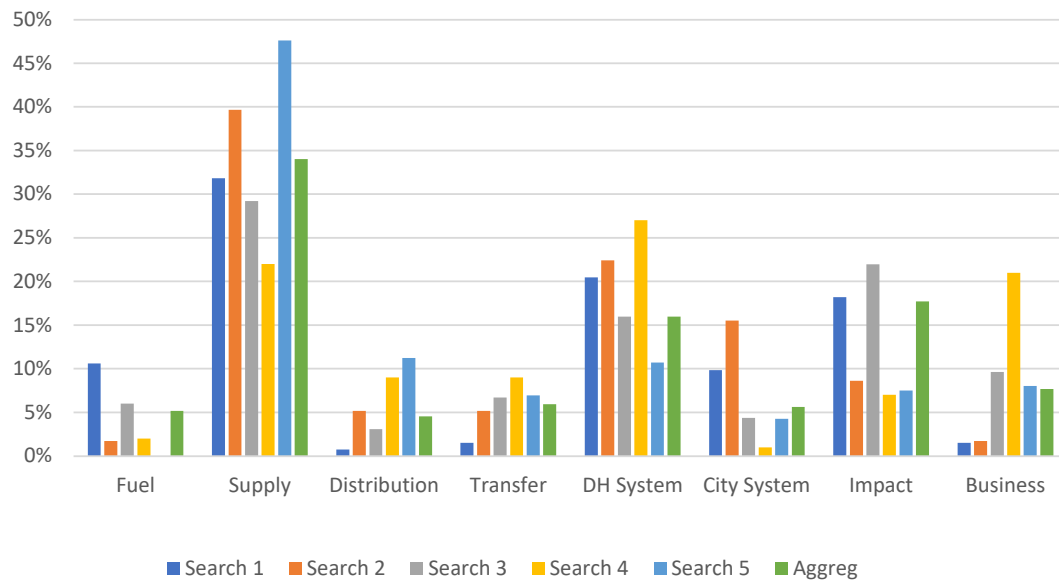


Figure 4. Distribution of articles. A summary of the search and coding in this review (see details in Section 2.2 Data Collection). The 8 groups are listed horizontally. The share, in percentage, of articles per search is shown on the vertical axis. The aggregated share from all five searches is also shown.

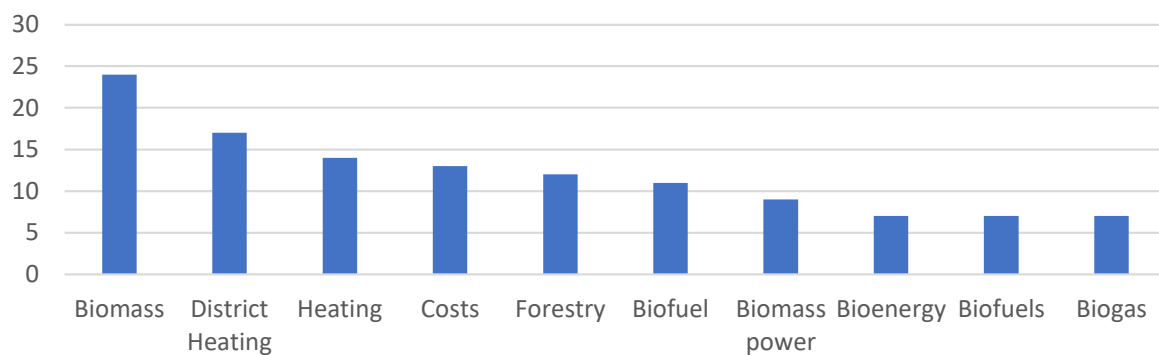


Figure 5. Fuel—most frequent keywords (horizontal axis) and the number of articles (vertical axis).

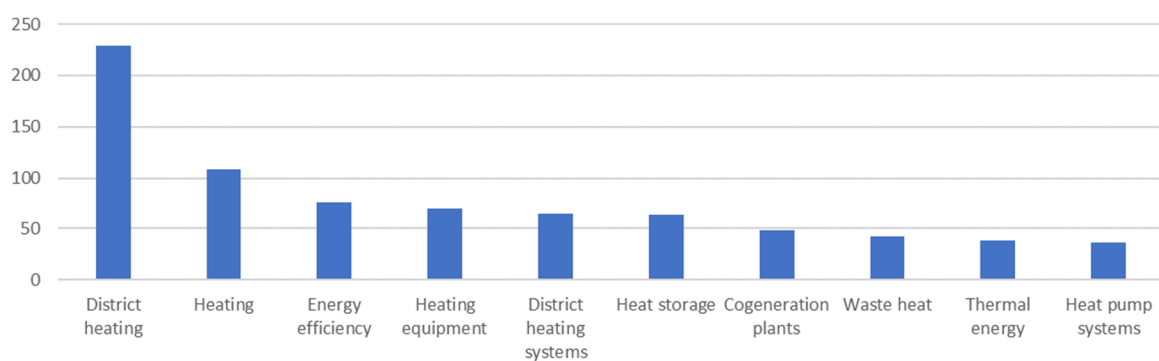


Figure 6. Heat supply—most frequent keywords (horizontal axis) and the number of articles (vertical axis).

By grouping keywords, seven sub-clusters were revealed (in falling order): cogeneration and combined heat and power (CHP), optimization and demand forecasting, heat storage, waste heat recovery, geothermal energy, heat and absorption pumps, solar energy, renewable energy and biomass. Regardless of the precise focus, two types of articles dominate.

The first type refers to articles that explore the feasibility and potential of specific supply and storage technologies from a system's perspective. The foci are on the systems analysis of plants and the supply of heat (production). One important aspect refers to a major challenge in all formerly centrally planned countries, and in some other countries too, to overcome the massive system defect of having two parallel energy systems: one for an electric power supply (using condensing power plants, with 30% fuel-to-power efficiency) and one for centralized boilers or boilers per building.

The second type refers to articles that develop supply and demand models for forecasting and supply optimization from a system perspective. The focus is on modeling the heat demand, which is balanced by the supply of heat. There are several commercial solutions for forecasting and optimization in this area.

Articles in this group are focused on the system level. The papers contribute to new insights about potential assessments, with few articles focusing on the process of innovation (The articles in the supply group have 2487 unique keywords. A scan, looking for specific keywords that indicate an innovation process, gave 222 such keywords that can be related to innovation. Analyzing the keywords indicated that there were few articles on specific heat and power technologies at the module and component levels [21].).

3.3. Group 3: Distribution

Heat distribution is the hot water distribution network, including pipes, pumps, valves, instrumentation and automation. Heat distribution is at the core of a DH system as it consists of the pipelines connecting heat supply plants with customers' heat transfer units. Typically, half of the capital employed for a DH company/organization consists of the distribution network. Based on experience (The cost to replace old pipelines varies from 300–10,000 euros per meter, with an approximative average of 1000EUR per meter. A pipe length of 500 km in a city gives a reinvestment cost of 500 million EUR.), and on [5], the reinvestment expense of the distribution network in a city with 100,000 inhabitants can be 500 million euros. Currently, European cities are facing billion of euros reinvestments to upgrade their aging DH infrastructure, built in the 1950s and onward.

The significant costs stand in stark contrast with a limited number of publications: it is the smallest group and holds 42 articles (4.7%). Where there is a potential for large cost savings, especially capital costs, there should be large incentives for innovation; hence the low number of articles is notable. Few articles in the distribution group are among the most-cited publications (search 1), indicating a limited scholarly interest.

The top ten keywords are listed in Figure 7. The keywords indicate that the publications are system-oriented or focused on the policy level, regarding energy efficiency, energy conservation and heat losses rather than on operational innovation.

By grouping a larger number of keywords, the two themes of "pumps" and "pipes" emerge. Of the articles, 67% are focused on research relating to new distribution networks, and the rest focused on existing networks. The articles focused on planning and network design (14), material (11), hydraulic engineering (11) and network monitoring (3).

To make sure that no important information on innovation was overlooked, the papers were coded a second time to further investigate which innovations are relevant, see Figure 8.

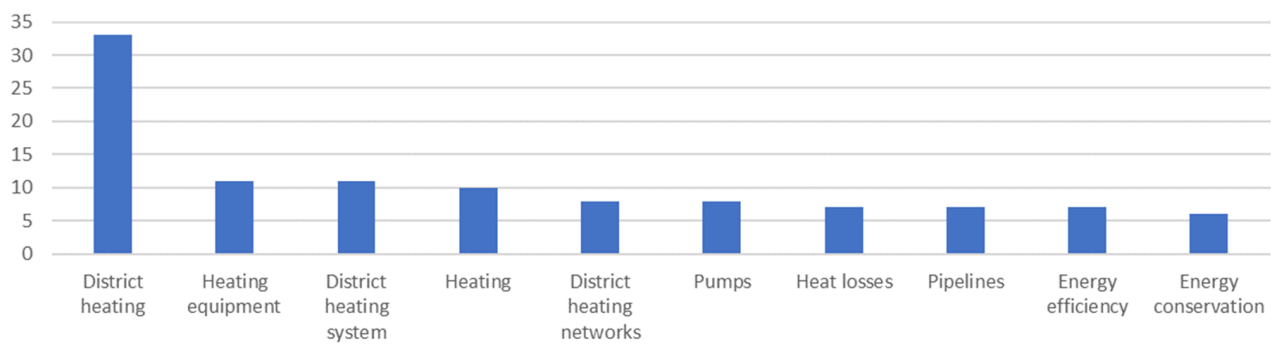


Figure 7. Distribution—most frequent keywords (horizontal axis) and the number of articles (vertical axis).

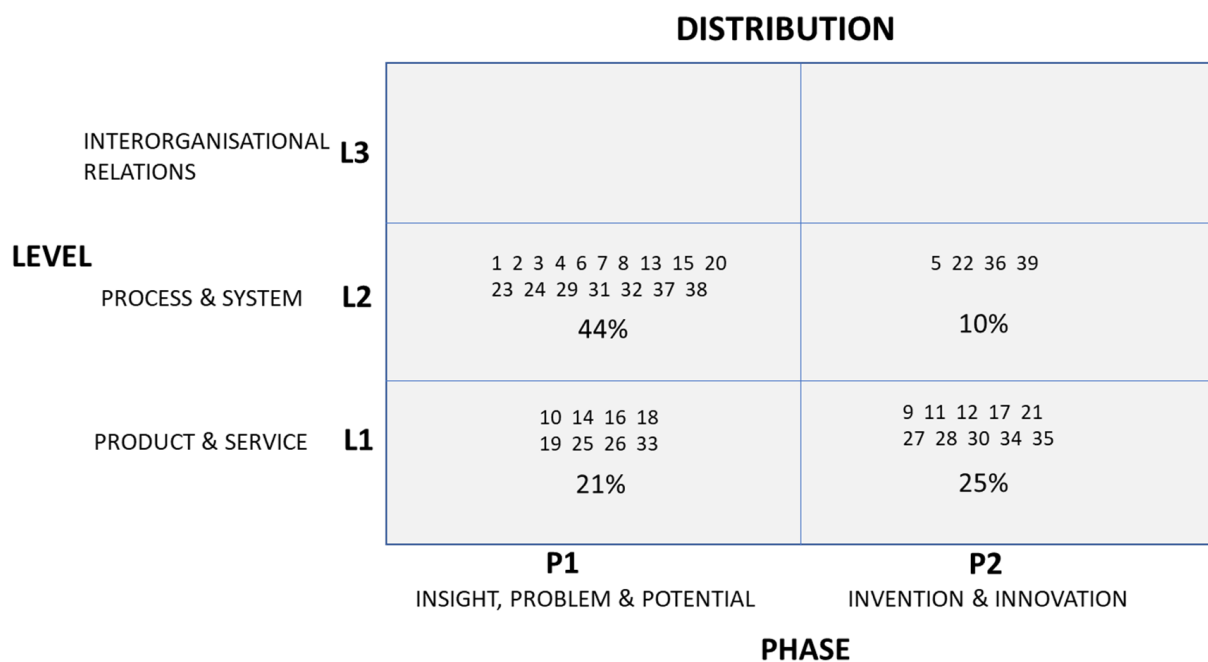


Figure 8. Articles plotted in two-dimensional of coding by phase and level. Each article is numbered, where the lowest number corresponds to the highest citation rate.

Of the articles, 44% were grouped into P1L2, which was the group characterized by the insight phase at the system level; and 21% of the articles were grouped into P1L1, the insight phase, on the product level. This means that two-thirds of the papers are oriented towards showing why the distribution networks are important. 25% of the articles were coded in P2L1, which is the innovation phase at the product level, and 10% are in P2L2, which is the innovation phase at the system level. Thus, around one-third of the articles related to innovation or an innovation process. No articles addressed the L3 level, which is the intraorganizational level and interaction with other infrastructure.

Further analysis of the 14 articles in the two innovations related groups (P2L1; P2L2) groups links six of the articles (5, 21 and 11, 12, 17, 35) to the new distribution networks, while the remaining eight articles are linked to the innovation of existing distribution networks and increased revenue or reduced costs (profit and loss statement), see Figure 9. The latter articles are published in a limited timespan (2017–2018), with five out of the eight articles being conference papers from the same conference. The main theme in four of the articles is monitoring and data analytics. Two articles bring up heat supply bottlenecks, which are capacity problems in the distribution network.

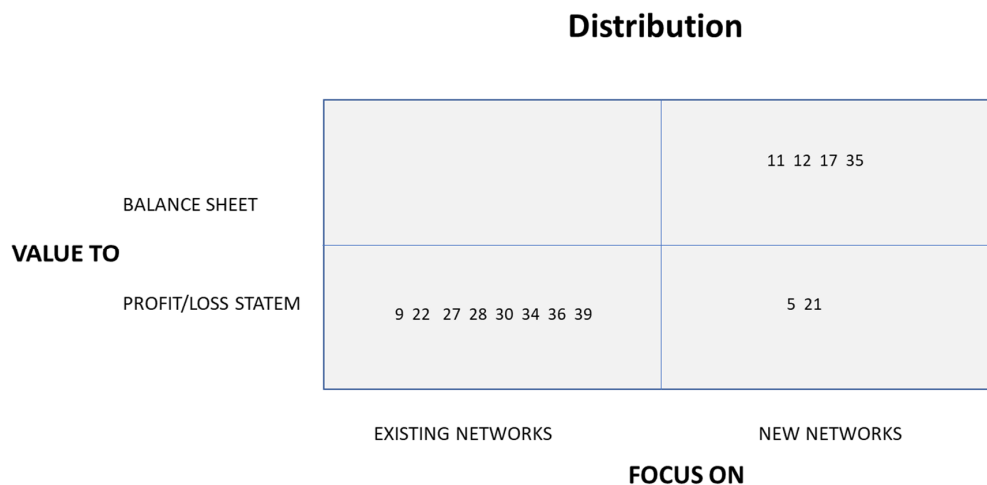


Figure 9. Articles plotted in two dimensions based on the type of value that is created, involving either improved Profit and loss statement or reduced capital employed (balance sheet). Each article is numbered, where the lowest number corresponds to the highest citation rate, as in the previous figure.

Four articles (11, 12, 17, 35) in Figure 9 focus on new networks and installations, dealing with improvements to the balance sheet by reducing the investment cost or extending the lifetime of the assets:

- Improvement of corrosion resistance for steel pipeline in the manufacturing process [22];
- Accelerated aging tests of the foam in the DH pipes [23];
- Using tunnel drilling technique, which involved the trenchless laying of pipes [24];
- Mechanical characteristics and influence of soil when laying new pipes [25].

The two following articles (5, 21) in Figure 9 focused on new networks, aiming to create value to the profit and loss statement:

- Mass flow control, ring topology for new networks, in order to reduce operating cost [26];
- Improved production methods for pre-insulated pipes [27].

It is remarkable that no article is focusing on existing networks and value to the balance sheet in an asset and infrastructure intensive industry such as DH. No article could be traced to a potential radical innovation.

3.4. Group 4: Transfer

Transfer (6% of all articles) consists of the interface between the distribution network and the customers' secondary heating systems of the buildings. Heat is exchanged from the DH system, via a heat transfer unit, to the customers' secondary heating system. Most heat transfer units are owned by customers and not by the DH companies.

The ten most frequently used keywords are listed in Figure 10.

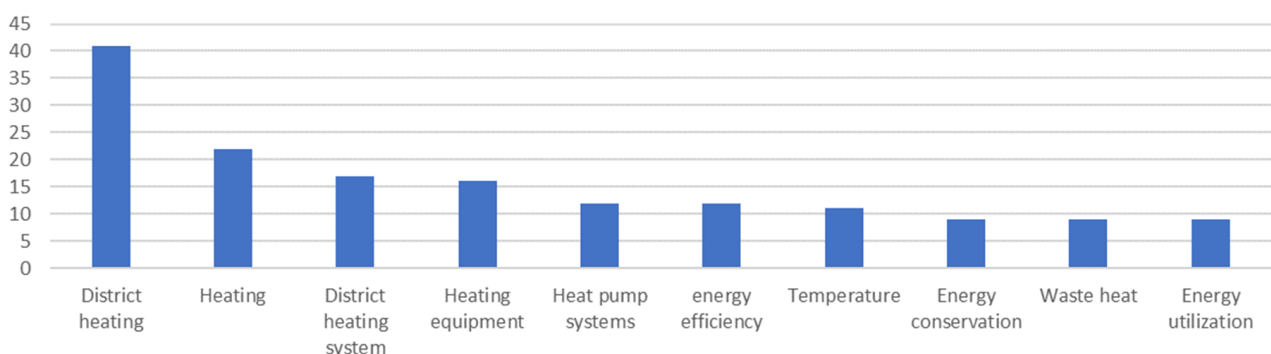


Figure 10. Transfer—most frequent keywords (horizontal axis) and the number of articles (vertical axis).

From the grouping of the keywords, the major themes of the transfer group were heat pumps, waste heat capture, heat exchangers, buildings, pumps and heat storage.

To trace innovation-oriented papers, the second level of coding was performed. The results are illustrated in Figure 11. Of the articles, 55% belonged to the P1 groups (insight), with 33% at the system level (P1L2) and 22% at the product level (P1L1). Further to this, 33% of the articles were coded in the innovation phase (P2) at the product level (P2L1). In the P2 column, 6% were coded at the system level (P2L2) and 6% at the inter-organizational level (P2L3).

		TRANSFER	
LEVEL	INTERORGANISATIONAL RELATIONS L3		12 29 32 6%
	PROCESS & SYSTEM L2	4 13 16 21 24 28 35 36 39 40 41 43 44 46 47 51 52 33%	2 5 53 6%
	PRODUCT & SERVICE L1	6 23 25 31 33 34 38 42 45 49 50 22%	1 3 7 8 9 11 14 15 17 18 19 20 26 27 30 37 48 33%
		P1	P2
		INSIGHT, PROBLEM & POTENTIAL	INVENTION & INNOVATION
		PHASE	

Figure 11. Coding of articles according to phase and level. Each article is numbered, where the lowest number corresponds to the highest citation rate.

To further analyze the innovation-related articles in the three P2 boxes in Figure 11, the articles were divided into groups that were based on whether they focused on existing or new systems, and whether they dealt with providing value to customers or DH systems (production), see Figure 12.

		TRANSFER	
VALUE TO	DH SYSTEMS (PRODUCTION)	1 3 5 7 8 11 14 15 18 20 26 27 30 48 53	2
	CUSTOMER	9 12 17 19 29 32 37	
		EXISTING SYSTEMS	NEW SYSTEMS
		FOCUS ON	

Figure 12. Articles from the three groups that arose from further analysis of P2. The analysis was in two more dimensions: the value, which was primarily based on the customer or to the DH system (production); and focus, looking at whether they were new systems or existing systems. Each article is numbered, where the lowest number corresponds to the highest citation rate, as in the previous figure.

22 out of 23 articles primarily focused on existing systems (see Figure 12). Seven (lower-left box in Figure 12) focused on value to customers:

- A review of smart meters and value to customers [28];
- Improved wastewater treatment using DH in the process [29];
- Building controller for improved customer satisfaction [30];
- DH applied to domestic hot water preparation in Chinese multi-story buildings [31];
- Designed algorithms for a mobile app to educate customers on how they influence the environmental performance of the DH system [32];
- Building automation to improve customer satisfaction and heat trading model [33];
- Developed method for detecting malfunctions in customer heating systems [34].

There were three categories of focus for the remaining 15 articles (top-left box in Figure 12), which dealt with improving the DH system and its production in existing networks.

The first and largest of the categories looked at temperature reduction (forward flow and return flow) in the hot water distribution and heat transfer to customers, including methods for fault detection in heat transfer substations. There are eight articles in this group, for instance [35,36]. Ref. [37] introduced methods to detect faults in the heat transfer interface to customers, which interfered with the reduction of system temperatures, which was followed up by [38] by using machine learning. Demand-side booster heat pumps were analyzed by [39,40].

There are three articles in the second category that involved the use of distributed absorption heat pumps, which were driven by heat from a high-temperature DH network that supplied heat to secondary heat networks. The idea is novel, potentially radical innovative, but no further publications were detected [41–43].

The third category consists of two articles that investigated buildings as short-term thermal energy storage. The first study was by [44], which was followed by [45].

Innovations in existing DH systems can, in most cases, also be applied to new DH systems. In 2012, Ref. [35] published article 2, the only article in the “new systems” fields in Figure 12. This was before the concept of 4GDH was established. The study simulated a low-temperature DH system, as well as the type of heating required in the secondary heating system in the buildings.

In summary, there are few articles that focus on customer-driven product and service development for new methods of heat delivery. An early study on demand-side management, using the buildings as thermal storage, was made by [44].

3.5. Group 5: DH System

This group focuses on the DH system, which is a systemic perspective of fuel input, involving the interaction between supply plants, the distribution network and the delivery and exchange of heat to the heat transfer substations. Each DH system is unique but is rarely delivered as a turnkey system.

There were 148 articles that were coded into the DH system group, corresponding to 16% of the total number of articles and placing this group among the top three.

The top ten keywords are listed in Figure 13.

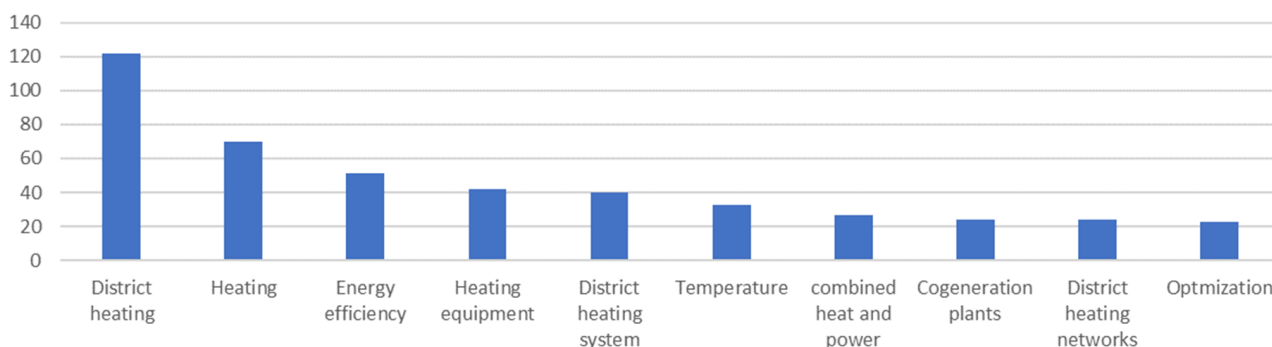


Figure 13. DH systems—most frequent keywords (horizontal axis) and the number of articles (vertical axis).

Based on the grouping of the keywords, the most common themes (in descending order) are low-temperature systems, combined heat and power (CHP), optimization and modeling, renewable energy, sustainability, smart energy systems, heat storage, waste heat utilization, pumps and geographic information systems (GIS).

Most of the articles in this group are focused on the early phases, in that they identify problems, opportunities or potential, pointing out a position or direction, or contribute new insights.

Historically, as publications show, innovation has been developed at the component level. 3GDH introduced pre-insulated and manufactured pipes and preassembled transfer substations. The concept of 4GDH was introduced in 2014 [46], the most cited article in the entire analyses of all groups. The 4GDH research platform has published several frequently cited articles, mostly positional and directional articles. Ref. [47] focused on merging electricity, heating and transport sectors in a “smart energy system”. Ref. [8] reviews the international position of DHC.

4GDH moves focus away from external fuel to internal heat captured in the supply process (surplus heat, solar, geothermal). From an innovation perspective, the technical change is incremental for the actors in the that studies are involved with the minor lowering of distribution temperatures. Radical innovation that changes the DH system or components is rare.

In the literature, there is not yet a consensus on whether 5GDH exists; while some claim it does, such as [48], others state that modern DH systems are subgroups of 4GDH [49]. However, by introducing demand-side heat pumps (5GDH) and energy storage, the system architecture in a DH system is changing more drastically. A radically lowered system temperature is enabled, which allows for a much greater capture of urban surplus heat and decentralized energy storage. The technical innovation is therefore expected in the distribution and heat transfer section of the value chain. 5GDH is moving the focus away from central supply processes to decentralized heat capture, from the heat distribution and transfer processes. Ref. [39] described an ultra-low-temperature DH, using heat from the return flow of an existing DH network.

3.6. Group 6: City System

This group contains articles that focus on DH within the urban setting, including aspects beyond heat supply.

There are 52 articles (6% of all) in the city systems group. The top ten keywords are listed in Figure 14.

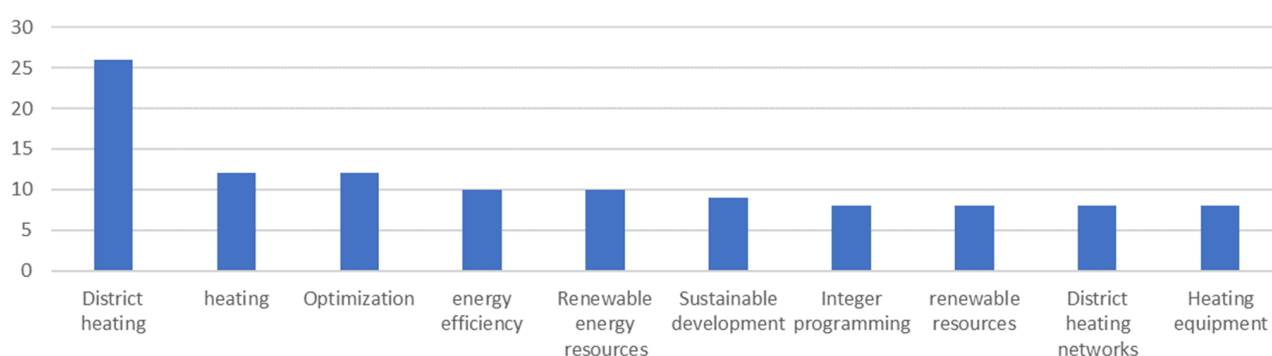


Figure 14. City systems—most frequent keywords (horizontal axis) and the number of articles (vertical axis).

It is difficult to find clusters (patterns among the keywords) due to the vast variety of keywords. However, when keywords are grouped, the following terms emerge optimization, energy efficiency, renewable energy, electric generation, sustainability, energy systems, energy storage, heat pump systems, smart energy systems and energy policy.

Geidl and Andersson [50] studied optimized power flow, gas, electricity and DH. Mathiesen, Lund [47] had a similar scope (smart energy systems), based on 100% renewables. Energy infrastructure industries are integrated with transport energy.

Among the 52 articles, there are four articles that reach outside the energy sector (DH, gas, electric power). Florentin [51] is the only article studying cross-utilities, including water distribution.

3.7. Group 7: Impact

This group includes articles that analyze the impact of DH in terms of how its use affects the customers, the environment and the local society.

With 164 articles (18% of all) in this group, it is the second largest. Many articles in this group aim to justify and motivate the concept of DH and cooling from a European perspective by demonstrating the benefits of DHC.

The top ten most common keywords are listed in Figure 15.

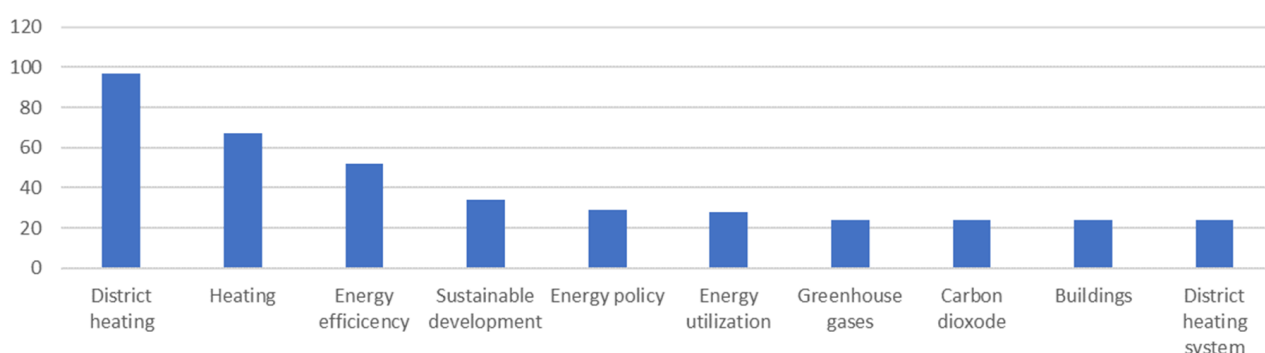


Figure 15. Impact—most frequent keywords (horizontal axis) and the number of articles (vertical axis).

Four major groups of articles were identified by keyword grouping: sustainability, policies, renewable energy and cogeneration. Sustainability typically means that it is environmentally sustainable. Policies refer to public policy instruments, taxes and legal restrictions. Cogeneration is a synonym for combined heat and power (CHP).

Examples of highly cited publications that are linked to the most common groups are [52], sustainability; [53], policies; [1], renewable energy and [54], Cogeneration.

By comparing the searches, there is a decrease in the number of articles during the last three years, which may be confirmation that DHC has been recognized at the EU-level, which is indicated by the [2].

3.8. Group 8: Business/Social Science

Articles in this group look at DH from a business or financial perspective, not from a technical, engineering or natural sciences perspective. There were 71 articles (8% of all) that were coded into the business, economics and other social science segments.

The top ten keywords are listed in Figure 16.

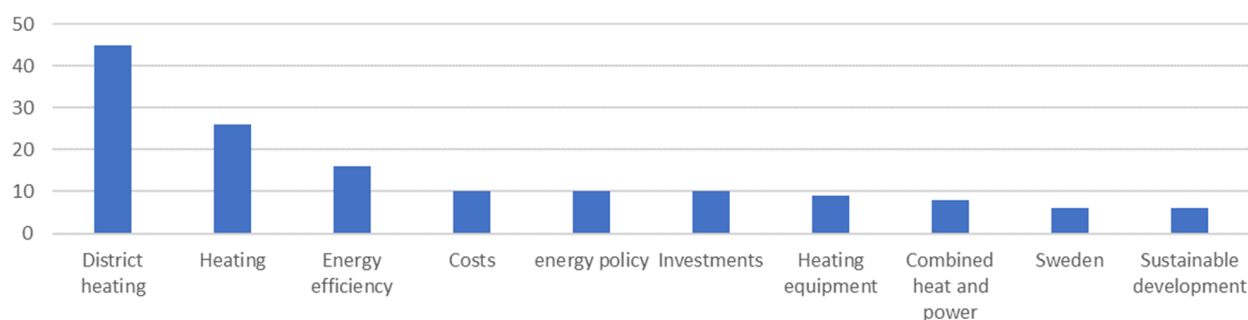


Figure 16. Business—most frequent keywords (horizontal axis) and the number of articles (vertical axis).

Economics and policies are the dominant themes that are observed after grouping the keywords. Only a few articles in this group are among the most cited.

Of the 71 articles, 19 focus on innovation. The remaining articles focus on policy instruments or finance/investment. Among the 19 innovation articles, there is one article that looked at innovation ecosystems [55], eight articles focused on large technical systems, transition, diffusion and adoption of new energy systems in terms of actors' collaboration [56]. Four articles focused on business model innovation [57], and six articles focused on new product/service development.

Of the 71 articles, eight include partial problem analysis and description of the challenges to the DH industry [58–60].

3.9. Results in Summary: All Groups

By summarizing the ten most common keywords from all nine groups listed above, we get a weighted result, which favors the small group keywords, see Figure 17.

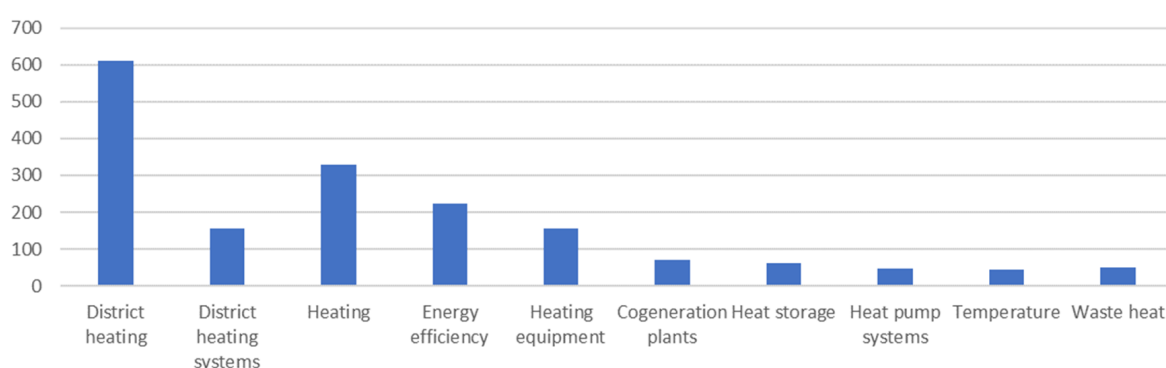


Figure 17. All groups—most frequent keywords (horizontal axis) and the number of articles (vertical axis).

Besides the obvious keywords, such as DH, DH systems and heating, we see energy efficiency, which is a fundamental justification for DH. We also see cogeneration plants, heat storage, heat pump systems and waste heat, which are all supply related. Heat pump systems relate to DH in three ways: heat pumps as a competing system to DH centralized DH supply with heat pumps or decentralized heat pumps at demand-side (5GDH). Heat storage is among the ten most common keywords, being in 167 out of the total 899 articles, which have the word “storage” in the titles, keywords or abstracts. The distribution per year is seen in Figure 18. 2018 has the most articles that have the word storage, with a steep increase compared to the previous years. As a comparison, the same type of search for the word “customer” gives 36 hits, “digitalization” gives one hit [61], “lean” gives 33 hits, “industry 4.0” has zero hits, “hydrogen gives 5 hits, and “BECCS” gives 2 hits.

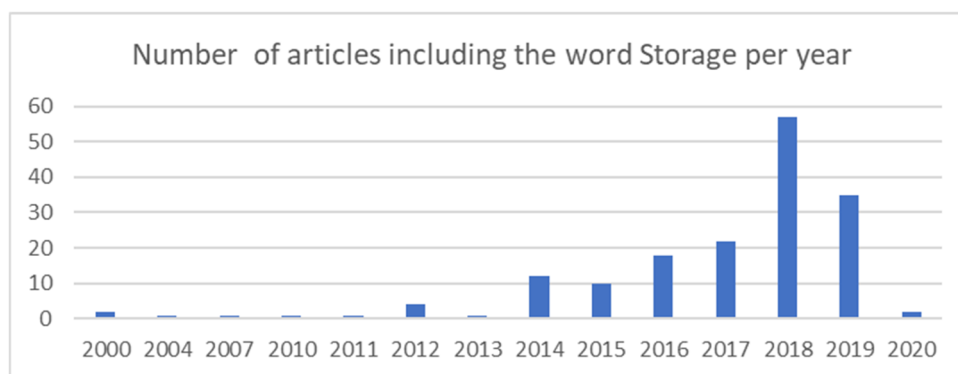


Figure 18. The appearance of the word “storage” in the abstracts, titles or keywords among the 899 articles (the total population of articles). Appearance per year (horizontal axis) and the number of articles (vertical axis).

Romanchenko, Kensby [62] and Vandermeulen, van der Heijde [63] compared central thermal storage with heat storage in buildings. Fleuchaus, Godschalk [64] reviewed aquifer storage. Vanhoudt, Clessens [65] analyzed three types of storage: central storage, decentralized storage (vessels in buildings) and thermal mass of buildings. Song, Wallin [66] analyzed the cost benefits of introducing demand-side thermal storage, in a temperature range of 40–90 °C.

4. Discussion

The results showed that many articles were focused on gaining insights, analyzing an innovation potential or a problem, highlighting development directions or quantifying the potential environmental impact of DH. These studies demonstrate an innovation potential, which eventually may lead to innovation. At the same time, the articles are not directly linked to innovation, as illustrated by the common keywords, such as heat losses, energy efficiency and energy conservation. Papers using these keywords tend to have a macrolevel perspective in regard to focusing on societal or environmental implications. In contrast, words like “hot water losses” focus on issues and challenges for individual organizations or the DH sector and are more directly linked to innovative solutions or innovations, even if they are not found to be as common as other keywords.

From the review, and in line with an IEA report [67], we conclude that DH has not been an innovative industry. IEA listed 100 top-priority innovation gaps across 45 key technologies and industries, but DHC is not mentioned. The DH industry tends to rely on political interference, which can be explained by strong public and municipal heritage. The drive to innovate is often linked to direct exposure to competitive market conditions.

The main driver for DH change is the slow but steady lowering of distribution heat temperature. During the last century, there have been improvements and efforts to reduce the distribution temperature, which have resulted in improved reuse of heat, decarbonization and local resilience. In addition, a more careful analysis indicates that different improvements in components, pipes, assemblies, materials, fuel and heat sources have shifted the technologies of the industry.

By analyzing the eight groups and the most cited articles over the selected timeframe, we have identified three ongoing and emerging major system shifts. First, the results confirm the shift from fossil fuel-based DH to renewables and in particular to nonfuel-based renewables such as solar, geothermal, surplus electricity (electric boilers) and capture of surplus heat [68,69]. This is linked to an increased interest in DH as a storage solution (flexibility provider to the energy system as a whole), but also in storage solutions for DH. A decline of interest in biomass as a renewable fuel was detected, although bio-energy carbon capture and storage (BECCS) is emerging, and BioCHP is seen as a key contributor in the electric power system. The decarbonization challenge is well covered in that the research community has been very clear in pointing out alternatives to fossil fuels, how to operate new plants and the importance of CHP in terms of energy efficiency and conservation. The issue is shifting towards the implementation of cleaner technologies, meaning that the risk exposure of purchasing fuel, which has always been significant to the industry, is reduced.

Second, introduced by Lund, Werner [46] and followed up by Lund, Østergaard [70], 4GDH and the following stream of articles point towards capturing of sources of decentralized surplus heat, which may indicate a shift of industrial focus from supply plants (production) to a focus on distribution and trading of heat. The shift implies that the 10-year lock-in to high-temperature secondary heat systems is being unlocked. Increased use of existing components, such as controllers, circulation pumps and radiators, will enable the shift. For most heat customers, such as owners of dwellings, public buildings, and offices, it is reasonably easy to adapt to using lower temperatures, but it can be more problematic for industrial users. Customers that cannot adapt to lower supply temperatures may demand new services or business models that offer a tailored top-up heat supply, from booster-boilers or heat pumps. From an economic perspective, the risk exposure is expected to decrease when the share of purchased fuel decreases and when the DH

company limits its investment in the production of heat instead of resorting to surplus heat generated by the fixed assets of other parties. However, the switch to increased surplus heat usage increases the risk of the waste heat source being terminated and of interacting with stakeholders outside of the own operational control.

Third, ultra-low temperature DH systems, sometimes referred to as 5GDH (The denominations 1, 2, 3 and 4GDH are academic constructs. 5GDH is a newcomer, if not being a subset of 4GDH or of a wider low-temperature group. We do not take a stand in this dispute but refer to publications [48]. The distinction resides in that 5GDH distribution operates below the legionella temperature legislation, which is around 60 °C and must use front-end heating. Usually, customer connected heat pumps, which is often an electrical-driven compressor.), where temperatures below 50 °C or lower is open for prosumer models and the heating and cooling is captured and exchanged in the same system, is increasingly clear, see, e.g., [48,71,72]. The emergence of ultra-low-temperature DH is not new, and it can be found in the literature since the 1980s. With such solutions, local energy storage will be more important to minimize the heat pump electric consumption and power demand peaks. Examples include building-type hot water accumulators and utilization of thermal mass in buildings.

From a functional perspective, there are two main differences between the second and the third trend. Ultra-low temperatures allow for new system boundaries and require new “active” components and technologies, such as front-end heat pumps, heat storages and customer engagement, introducing a feature of interactivity in the DH system. In turn, this suggests that DH will be less of a standalone industry, with rather well-defined organizational barriers with fuel suppliers, and more of a building block of a more complex but (presumably) more efficient energy system. In addition, DH could become bidirectional, shifting away from distributing a flexible amount of heat from one place to another to delivering the right temperature (heating as well as cooling) to the right place. Indeed, it appears as if there is a nascent innovation in this increased interactivity that can strengthen the competitive advantage of DH in the future.

Surprisingly, examples such as local thermal storages by boreholes, greatly used by the standard heat pump applications, are not mentioned in the reviewed articles. This shift will make the system more flexible and dynamic but will require new technical solutions and much more of a supplier collaboration and customer focus. Comfort cooling for one customer generates excess heat that can be used as heat for another customer or stored in heat storage, which is a common application for heat pumps. The heat distribution network can gradually be transformed into a multisided trading platform [73].

We identify that a common denominator for the suggested shifts is asset management, a topic that is poorly covered by the literature. The advantage with DH (to redistribute heat) is a weakness from an economic perspective—unless the expected lifetime of the network is extremely long, on the order of 50–100 years. This means that a fundamental challenge for DH is the capital expenditure, with upfront investments in terms of affording new distribution networks or replacing the old. Underground pipelines in city centers are very expensive to build or replace. However, we argue that the shift will reduce cost and the risk of price fluctuation of fuels and reduce capital employed in large production plants. Given that ultra-low temperatures are open to entirely new heat sources, heat can be traded from many new sources and suppliers. At the same time, lower-system temperatures will make the distribution more error-prone to bottlenecks, which is a problem seen in power distribution. In particular, there is sparse research on how to manage and modernize existing assets, how to build new networks at radically lower costs or how to maximize the utilization of the assets.

In cities where DH is well established, it is standard to coordinate infrastructure investments when new areas are planned. Such coordination leads to significant cost savings. While reviewed articles explore broader energy systems, such as combinations of DH, electric power, gas and transportations, we have found only one article [51] with a focus on cross utility (Typical infrastructure in a city is power cables, water and sewage

pipings, optical fiber, occasionally gas, DH, DC and stormwater drainage.) coordination beyond the energy sector. Experience suggests that pipes make up about 20% of the total civil work cost in a DH pipe construction project. There should be a substantial synergy potential if costs are shared among all infrastructure owners in a new expansion or replacement project. The potential and obstacles for such an integrated city system are not explored in the reviewed articles, which is surprising.

Many research articles, listed in the group “impact”, have had the purpose of demonstrating the environmental performance of DH. For continued development, we find that both technical innovation (in the 5GDH context) and stakeholder innovation (foregone today) need to be addressed in an innovation framework.

5. Conclusions

Returning to the research question, we conclude that innovations have been responses to external change and have addressed what to do from a system point of view. The innovations have not been explicitly discussed as such but are a consequence of the continuous industry development. There is little research on DH internal challenges, and there should be a large potential to benefit from explicit research on innovation to manage the opportunities and challenges that lie ahead.

We find that the publications focused on what DH must do from a system or production perspective and why this is important. Common answers to what to do are—develop CHP and low-temperature systems. CHP should be developed because the system solution has superior energy efficiency and flexibility. Lower system temperatures lead to lower heat losses allowing more surplus heat to be captured, e.g., lower cost and environmental gain. The common denominator in the CHP and the low-temperature context is that incrementally improved energy efficiency is sought.

Most of the reviewed articles have a modest relation to innovation and do not show or discuss ideas on how to develop DH, especially in terms of *who* should do it and *how*. For example, how should DH be developed in cities such as London, Brussels and Madrid? Who should do it? How should DH be modernized in Berlin, Stockholm and Copenhagen, and by whom? Can a transition be made from the current to the future DH? Hence, it is known what to do and why, but which (who) stakeholders can and should undertake innovations is not identified. Therefore, while the macro perspective identifies the directions that will continue to be important, more research will be needed on how firms or organizations develop DH and who should do it. The shift is an expected outcome from “this is what we must do and why” to “this is how to do it and by whom” in part driven by the ongoing decrease in water temperature, allowing for more types of actors being involved in DH.

We conclude that the sector has not applied the logic of innovation during development. This is especially reflected in the academic literature as the attention on who innovators are and how they innovate is limited. To remain competitive in the future, there are questions that need answers: How do we organize innovation internally and in collaboration? Who are the innovators, and what resources and capabilities are required? A better understanding of the innovation processes applied to the sector could generate substantial value.

Venues of future research could be to analyze how a broader and integrated city utility perspective relates to other infrastructures, below and above ground. Is there a hidden synergy beyond existing collaboration that can reduce the need for subsidies to construct new networks? There is the potential of new research beyond energy systems, for instance, on asset management aspects and innovation in the technology supply chain, focusing on innovative tech companies and their needs.

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Abbreviations

1GDH	First-generation DH
2GDH	Second-generation DH
3GDH	Third-generation DH
4GDH	Fourth-generation DH
5GDH	Fifth-generation DH
CHP	Combined heat and power
DC	District cooling
DH	District heating
DHC	District heating and cooling
DHS	District heating system
HDN	Heat distribution network
HTU	Heat transfer units

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