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Something is sustainable in the state of Denmark: A review of the Danish district heating sector

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ABSTRACT

This paper provides a coherent review of district heating in Denmark, exploring past, present and future perspectives. Danish district heating is known as unique internationally in terms of heat planning strategies, technical solutions and combinations, energy efficiency and sustainability, ownership models and financing, and it has captured the attention of district heating communities and stakeholders worldwide from the early days. Historically, a ban on landfills incentivised waste incineration, and the strategic integration of combined heat and power plants and recycling of waste heat from industry all increased energy efficiency in the energy system. Ultimately, this contributed to the top World Energy Council ranking of the Danish energy system according to the energy trilemma criteria. A cooperative mind-set, welfare state values and the notions of energy efficiency-, availability-, independency- and sustainability were all pivotal for the evolution of the district heating networks throughout Denmark. Other unique features of the Danish district heating sector include large-scale collective heat planning, the mandatory connection, the non-profit principle, the same approximate price for customers irrespective of heat density, and the relatively high average price of district heating. Moreover, district heating knowledge hubs have led to world-wide exports of district heating technologies and know-how. Future challenges for the Danish district heating sector include increasing biomass import dependency, the changing role of combined heat and power plants in the energy system, transitions to non-combustion heat supplies, and competition from individual heat pumps in single-family houses. However, future 'smart' thermal grids will increasingly facilitate sector coupling processes as more renewable energy resources are integrated into the energy system in Denmark and internationally.

1. Introduction and background

1.1. The fundamental idea of district heating

The fundamental idea of district heating is to use local fuel- or heat resources that would otherwise be wasted to provide heating for end-users [1]. Heat used for district heating may be waste heat from thermal power generation via combined heat and power plants (CHPs), waste heat from industry, recycled heat from the incineration of household waste, other low-quality fuels, and various sorts of biomass, for example waste wood from forestry [1]. District heating plants can also be powered by solar heating, geothermal heat, and wind power that feeds electric boilers [1]. Various short-term and long-term thermal energy storage solutions enable heat storage in the district heating systems, and this facilitates the integration of locally available renewable energy resources into the energy system [2].. In this way, district heating may increase the energy efficiency of the energy systems; district heating facilitates diversification and overall energy system flexibility. An overview of a district heating scheme is provided in Fig. 1.

1.2. Motivational drivers in the evolution of district heating in Denmark

The energy system in the small Scandinavian country of Denmark is ranked among the best in the world by World Energy Council (WEC) judging by the parameters of energy security, energy equity and sustainability [4]. The underground district heating infrastructures throughout the country are pivotal in this regard. The district heating market share in Denmark is among the highest in the world; it supplies approximately two thirds of Danish private households with space heating and domestic hot water [5,6].

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Abbreviations

4GDH	4th Generation District Heating
A.M.B.A.	Cooperatives with limited responsibilities
A.S.	Danish abbreviation for aktieselskab (limited company)
ACHP	Association of Danish CHP Plants
CHP	Combined Heat and Power
DBDH	Danish Board of District Heating
DEA	Danish Energy Agency
DH	District Heating
DHA	District Heating Association
DKK	Danish Crowns/Kroner
DUR	Danish Utility Regulator
EU	European Union
GDP	Gross Domestic Product
GWh	Gigawatt hours
HSA	Heat Supply Act
I·S.	Danish abbreviation for interessentskab (general partnership)
MJ	Megajoule
MWh	Megawatt hours
NGOs	Non-Governmental Organisation
PJ	Petajoule
WEC	World Energy Council
WtE	Waste-to-Energy

From the early days, the emergence and the evolution of the district heating sector in Denmark was motivated by the top-down and bottom-up pursuit of stable, available and affordable heating for all [7]. From the top down, the initial motivational driver for district heating was to achieve higher energy efficiency in the energy system by recycling surplus heat from thermal power plants. A second motivational driver was the pursuit of stable and affordable heat supplies throughout the country, including in smaller towns and villages. Highlighted by the global energy crisis in the 1970s, a third was the urgent need for reduced energy import dependency and energy diversification. Large-scale, long-term and collective heat infrastructure planning initiatives were kick-started throughout the country in the wake of the energy crisis [8, 9]. As environmental awareness gradually grew throughout the 1980s and 1990s, climate change mitigation became a fourth motivational driver, and energy policy ambitions now shifted to focus also on low-carbon energy transitions and sustainability. The fundamental characteristics and potentials of district heating systems already contributed directly to this growing environmental agenda.

Throughout the history of district heating, the Danish district heating sector has been looked to as a forerunner vis-à-vis district heating technologies, innovation, research, heat infrastructure planning and policy among international district heating communities. Yet, no comprehensive scientific review of the Danish district heating sector has been written (see Chapter 3). Indeed, within international academic energy research communities, the Danish district heating sector has lived a rather quiet and anonymous life. This paper seeks to close that gap within in the scientific literature.[1] Focussing on the socio-technical-, socio-political- and organisational aspects of the Danish district heating sector, this paper outlines the history of district heating in Denmark, describes the current state of the sector, and touches upon future scenarios for Danish district heating.

The research is guided by the following research questions:

- *What informed and inspired the deployment of district heating in Denmark historically?*
- *What characterises the technical, political and organisational perspectives of the Danish district heating sector, and how is this unusual or unique compared to district heating elsewhere, if at all?*
- *What future challenges and potentials might the district heating sector in Denmark face?*

At the heart of the research is the fundamental understanding that the energy system is more than technological assemblages and infrastructures, but that energy systems are deeply embedded into

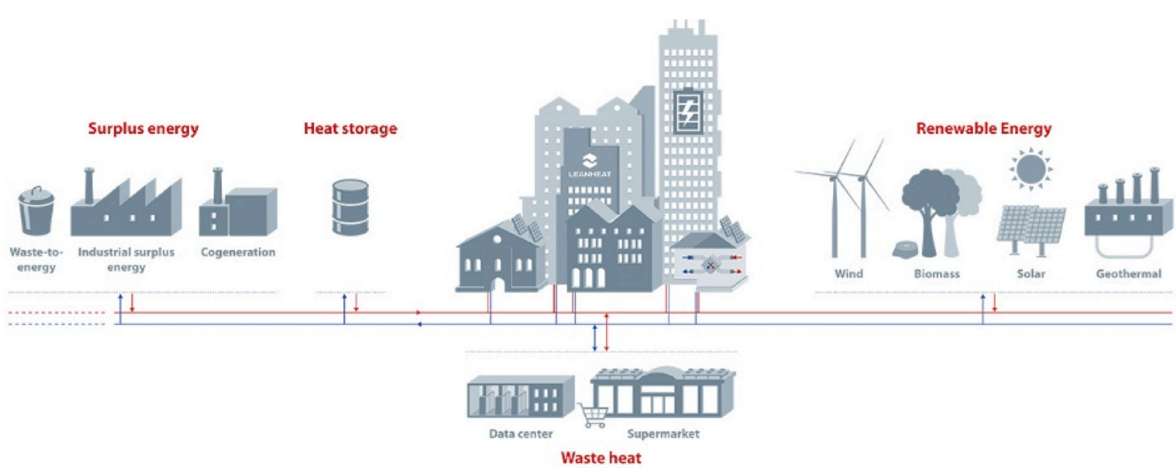

Fig. 1. The district energy scheme. Picture source: [3]. The red lines denote distribution pipes with supply temperatures, while the pipes with return temperatures are blue. Reprinted with permission.

[1] Thus, an additional purpose of this paper is to disseminate some of the rich district heating related body of knowledge found also outside of academia to the academic readership.

societies [10]. In terms of limitations, the ambition of providing a *trans*-sectorial overview of the Danish district heating sector, and the consequent scope of the paper, inevitably comes at the cost of in-depth detail.

The paper is organised in the following way: After the methodology section (Chapter 2), the literature review in Chapter 3 maps how the Danish district heating sector has been represented in the scientific literature and among international district heating communities. A brief introduction to the history of district heating in Denmark (Chapter 4) provides the background for understanding the current state of the sector. In Chapter 5, the *trans*-sectorial socio-technical overview describes the predominant technological- and infrastructural combinations, issues of planning, governance, institutional infrastructures and features of the energy market. Chapter 6 discusses future sector scenarios. Finally, Chapter 7 shares insights from the Danish experience and discusses future trajectories and challenges for district heating in Denmark.

2. Research methodology

The primary purpose of this research is to provide an overview of the Danish district heating sector. For this purpose, peer-reviewed academic literatures, sector reports etc. and expert insights are all invaluable, as they provide different sources of valid information.

Knowledge and knowhow among sector professionals and experts may not always be fully accessible to all researchers. Therefore, a secondary purpose of this research is to disseminate important insider knowledge from district heating sector professionals and experts to academic research communities. These ambitious research aims called for an innovative research- and review approach.

2.1. Methodological synthesis and interdisciplinary research enquiry

To accommodate the research aims, the final research design was informed by - and synthesised - the methodological research approach of scoping reviews and integrative reviews [11,12]. Scoping reviews provide an overview of research evidence. They 'describe existing literature, [other sources of information], and commonly include findings from a range of different study designs and methods' [13]. Integrative reviews may welcome 'experts as valid sources of evidence and as providers of continuous data collection and synthesis' [12]. Accordingly, this methodological synthesis facilitates the integration of knowhow- and insights generously shared by sector professionals and other experts into the carefully curated literature overview. Overall, the mixed methods research enquiry benefits from the strengths combining various sources of data [14,15]. Moreover, in drawing upon the different disciplinary traditions and bodies of knowledge represented in the research team, it also benefits from the strengths of interdisciplinary inquiry [12,14,16].

2.2. Data and data collection

The mixed research data were collected from the academic database, SCOPUS, and from district heating sector-specific knowledge repositories. Data also include sector reports- and documents, heat-supply related legislation, sector news- and media coverage. This key body of knowledge was supplemented by qualitative exploratory data collection in the Danish district heating sector carried out by the leading author. These data comprise informal-, semi-structured- and structured interviews [17–19] with internal- and external district heating sector professionals and experts, government employees and district heating researchers from academia. They also include participation in district heating sector workshops, seminars, and webinars.

This qualitative enquiry qualified and contributed to the literature review as informants referred to, mentioned or recommended literature and other bodies of knowledge they knew of and perceived as important. The quality and relevance of both primary and secondary sector documents was critically assessed by the author team, with the second author drawing upon professional expertise, insights, and intuition from a lifelong career as a district heating researcher and district heating professional.

The section below provides a brief introduction to the history of the district heating sector in Denmark.

3. District heating in Denmark: a literature review

3.1. The past: the early days

Denmark was the first Nordic country to implement district heating, and the country was at the forefront in Europe. An early implementation picture is provided as Fig. 2. In these early days of district heating in Denmark, a group of Danish engineers disseminated their insights from Danish district heating to engineers abroad. Examples of these short overviews are [20–22]. Several early papers also provided detailed information about CHPs in Denmark. These documented how CHPs were strategically integrated into the energy system (see, for example [23–27]).

In the 1960s, several international district heating experts visited Denmark to study the district heating systems in the country at the time. Their communications suggest that the Danish district heating sector was viewed as leading within the field (see British examples [28,29], and German examples [30,31]). Overall, this interest in and representation of Denmark among international district heating communities illustrates that the country had, indeed, been looked to as exemplary and inspirational.

3.2. The present: the state of Danish district heating

Judging by international comparisons, the Danish heat-planning system is unique in various ways. For example, Chittum and Østergaardstudy Danish municipal heat-planning practises, and examine how heat infrastructure planning processes are organised with the relevant heat-planning authorities, see [32]. The paper concludes that comprehensive heat infrastructure planning in Denmark has supported the development of cost-effective district heating systems. Shifts in Danish energy policy related to the ongoing low-carbon energy transitions in Denmark are examined in Ref. [32]. Focussing on energy flexibility, it explores the policy changes that affected the previous, strong support for Danish district heating.

Intervention strategies for socio-technical heat infrastructure transitions in Holland (from coal and oil to gas) and Denmark (from oil to district heating) are explored in Ref. [33]. In both cases, these socio-technical transitions were deliberately accelerated. The paper summarises lessons about intervention strategies facilitating rapid sociotechnical change. Decarbonisation of heat supply is also the main theme in Ref. [34]. Here, four different countries are described as forerunners vis-à-vis solar thermal, heat pumps, gas boilers and district heating. In this international comparison, Denmark was described as the district heating forerunner.

Several benchmarking studies use the Danish district heating sector as a reference case. For example, Ref. [35] provides a technical comparison of district heating systems in China and Denmark, and [36] compares district heating systems in Zagreb and Aalborg, identifying similarities, differences and potentials for improvement. In comparing large-scale solar thermal systems in four leading countries, Ref. [37] describes the Danish case as outstanding.

3.3. The future: forecasts and scenarios

Future perspectives for district heating in Denmark are also explored. Examining the role of district heating in the future Danish energy system, [38] concludes that district heating may contribute to increasing

Fig. 2. District heating construction works, Aarhus. Picture source: Affaldvarme Aarhus. Reprinted with permission.

the sustainability of the energy systems and ensuring the security of heat supplies, although substantial heat-saving measures should be installed. In studying Danish buildings that still use fossil fuels for heating, [39] recommends that some of these buildings should be connected to district heating, while the remaining buildings should use individual heat pumps. Conducting a survey to investigate stakeholders' perceptions of 'smart' district heating grids and the use of energy-flexible buildings, [40] concludes that work remains to be done on social aspects and regulatory issues relevant to maximising the future flexibility of district heating infrastructures.

A 2050 forecast of Denmark concluded that, in part, the costs of decarbonisation for Danish district heating systems could be covered via the economic benefits of using lower temperatures for heat distribution in the district heating systems [41]. This result was later confirmed in a case-study of low-carbon potentials for the district heating system in Aalborg [42]. A notable paper describes five future potentials of district heating systems, one of which is the ability to couple the different energy sectors within the future and increasingly integrated 'smart' energy systems [43] (see Chapter 6). Common to all these papers about district heating in Denmark is their rather limited aim and scope; for example, many are brief communications, technical assessments, heat planning studies, or benchmarking assessments, and they may focus on CHPs only, or on future perspectives and scenarios.

In summary, the above literature review documents that Denmark has historically been – and still is – viewed as a forerunner within international district heating communities. It also confirms that a comprehensive scientific review and overview of the Danish district heating sector remains to be done. This paper sets out to fill that gap in the scientific literature.

The following chapters - Chapter 4 (the past), 5 (the present) and 6 (the future) - outline what are considered as typical features of the Danish district heating sector within international district heating communities. The subheadings in each Chapter highlight the main topics or trends of international interest.

4. The past

4.1. The emergent welfare state and the cooperative spirit

This brief historical account shows that the current scale of the district heating networks throughout Denmark may ultimately be viewed as the result of historical events, and the interchange of cultural, social and political values and rationales, bottom-up innovative drive and top-down support.

The first primitive CHP in Denmark was built in the then working-class municipality of Frederiksberg in 1903. This Waste-to-Energy (WtE) plant combusted household waste and solved the pressing municipal problem of waste disposal given the lack of available land for landfills. This WtE plant supplied nearby municipal institutions with heat. In the following decades, district heating technologies improved, and district heating facilities emerged throughout the country [7,44,45].

The Danish culture of cooperative ownership, particularly from the agricultural sector [46,47], translated easily to the heat sector. Mainly in the rural areas, local initiative groups jointly invested in cooperatively owned district heating plants to ensure a stable supply of local heating [7,45]. Political wiggle room for experimentation and creative minds encouraged this local innovative- and problem-solving drive [7,46,48]. The Danish population grew after the World Wars, and with it the suburbs, material consumption, and national levels of energy use [49,50].

In the '50s, the public sector grew, and local councils were obliged to provide a stable and affordable energy supply for all [51,52]. In urban areas, some municipalities (sometimes jointly) invested in larger centralised and energy-efficient CHPs. Oil was readily available, inexpensive and easily transportable, and therefore the prioritized fuel [45,53]. Viggo Kampmann (prime minister of Denmark from 1960 to – 1962) introduced the notion of the Danish welfare state, celebrating the equal social rights of all citizens, rich and poor. Social welfare included all sectors of society [54].

The energy sector expanded at an astounding pace throughout the 50s and 60s, and the underground district heating network took in new territories (see Fig. 3 and Fig. 4). As these district heating networks slowly stretched their underground fingers throughout the country,

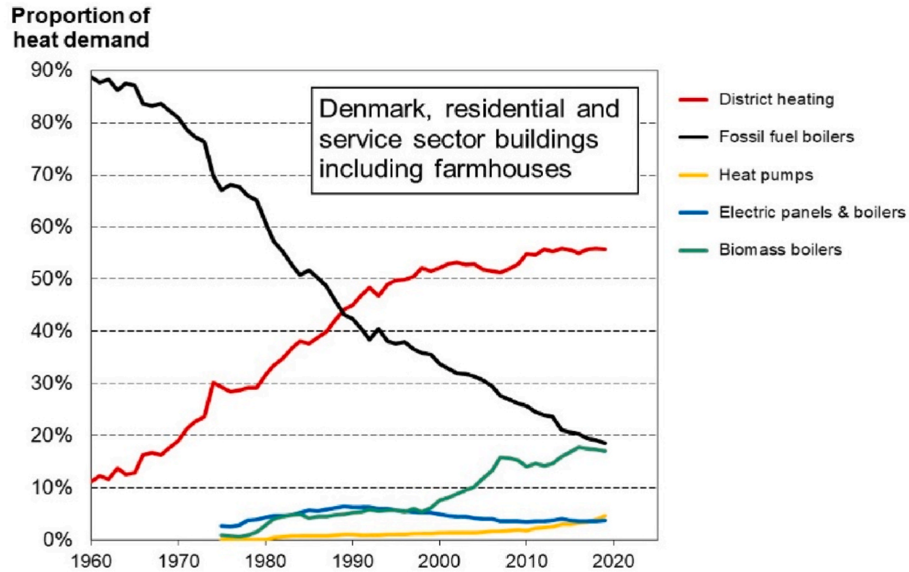

Fig. 3. Heating methods in the total Danish building stock 1960–2019 by proportion of total heat demand. Industrial buildings are not included in this diagram. Data source [55].

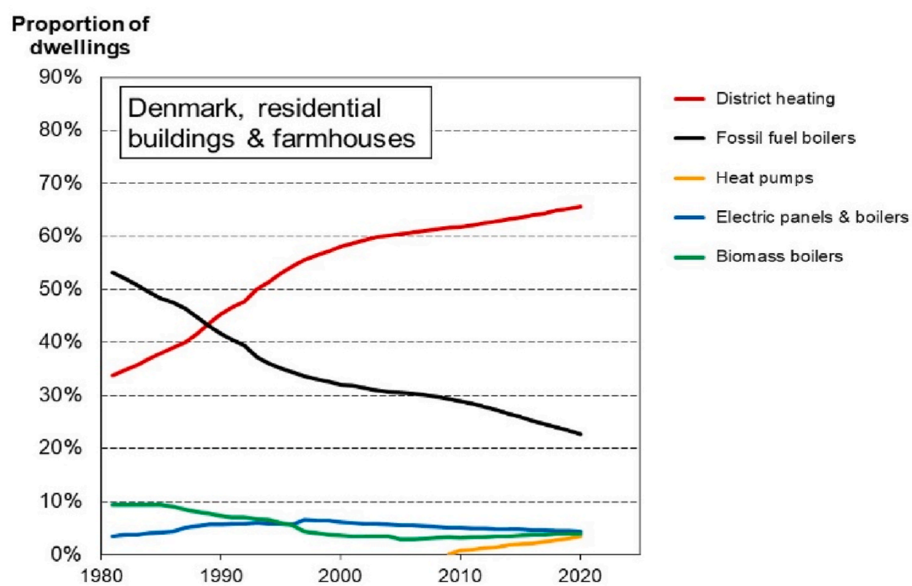

Fig. 4. Heating methods in Danish residential buildings 1981–2020 by proportion of dwellings. Data source [56].

values integral to the Danish welfare state itself [52] became intimately intertwined with the district heating sector. With time, this synthesis of welfare state ideologies and the cooperative mindset and values became inscribed into the norms and principles of the Danish district heating sector. Meanwhile, explorations for natural gas in the Danish North Sea commenced [8].

4.2. 'No' to nuclear, 'yes' to large-scale collective heat infrastructure planning

In the '70s, Denmark was almost 100% energy import dependent. The global energy crisis was devastating for the country. The economy suffered and unemployment soared. The crisis was a wake-up call for the Danish authorities. Shorter-term government remedial measures included the so-called car-free Sundays. Longer-term strategic energy planning and policy was kick-started in the wake of the oil crisis [8,49,50,57].

To reduce energy import dependency in the country, the Danish Energy Agency (DEA) was established in 1976 with the task of developing longer-term energy planning and policy initiatives. The results of this work were broadly captured by the headlines: energy independence, fuel diversity and energy efficiency [49,50]. The first Danish Energy Policy was adopted in 1979, and the 1979 Danish Heat Supply Act [58] provided the legal framework for the large-scale collective heat infrastructure planning initiatives ahead. The heat infrastructure planning strategically integrated CHPs further into the Danish energy system. The heat supply areas for district heating and the Danish North Sea natural gas were also mapped via a nation-wide planning process referred to as 'zoning' [8,9,57,59,60].

The future roadmap for the Danish energy system was not yet final, however. The question of nuclear power lingered. In Denmark, the public antinuclear movement gained momentum, and it was particularly active during the energy policy negotiations in the late '70s. The anti-nuclear movement called for the integration of renewables into the Danish energy system as alternatives to nuclear power (see Fig. 5) [8,61]. In 1985, the Danish government finally voted against including nuclear in the future Danish energy system [8].

4.3. Renewable energy resources and decentralised CHPs

Environmental awareness and concern increased throughout the '80s and '90s, both nationally and globally [7,8,48,57,62]. The Danish government published the Energy 2000 Action Plan in 1990, the first low-carbon energy transition strategy in the world. This energy plan prioritized the integration of renewable energy resources into the Danish energy system and planned for phasing coal out of the system. The heat infrastructure planning initiated after the energy crisis was more or less complete in 1990, and the principles for future heat planning had been determined. Heat planning was decentralised and would take place on a project-to-project basis going forward. Local municipal councils were now responsible for ensuring that future heat infrastructure projects were carried out in accordance with the ministerial criteria [63]. The rationale for decentralisation of heat infrastructure planning was that increased ownership of local heat-planning initiativeswould strengthen the integration of local ideas and initiatives in municipal heat planning practices [8,64,57].

The district heating networks were extended with decentralised CHPs in the '90s. These were typically fuelled by natural gas and situated in areas of relatively low housing density. Some became known as 'bare field plants'. At the outset, their economy was sensible, but when the price of natural gas increased unexpectedly, the economy of the bare-field plants suffered. The Danish government later subsidised these decentralised bare-field plants via numerous aid packages [65,66].

In 1997, Denmark became the first country in the world to completely ban the landfilling of combustible waste, and this became a strong driver for WtE [67]. Moving into the 21st century, large ratios of renewable energy resources, most notably biomass, were swiftly integrated into the district heating systems. The increasing biomass demands were met by large-scale international biomass imports [8,62]. This will be further explored in section 5.3.

In brief, local initiative and drive, the cooperative culture and values, a pragmatic approach to solving societal heat supply challenges, welfare state values, the global energy crisis, top-down heat infrastructure planning, antinuclear public sentiments and, later, growing environmental awareness and concern all contributed to the emergence and evolution of district heating networks throughout urban and rural Denmark. The global energy crisis and antinuclear sentiments called for a *diversity* of energy resources as *alternatives to imported fuels, such as*oil and nuclear power. Growing environmental awareness in the following decades shifted this emphasis to the focus on *renewable* energy resources in the energy mix as *alternatives to fossil fuels*. In this way, the small country of Denmark granted itself a head start in the race towards a low-carbon energy transition.

5. The present

This chapter describes the contours of the Danish *district heating landscape* (see Fig. 6).[2] It outlines the diversity of district heating infrastructures, technical solutions and combinations, fuel-use strategies, supply-area characteristics, and pricing and ownership models [68,69]. It also outlines the key legal principles for district heating in Denmark, describes the sector organisation and touches upon market perspectives.

[2] The focus of this review and overview paper is first and foremost socio-technical-, socio-political- and organisational perspectives of the Danish socio-technical district heating landscape.

5.1. Energy supplies, district heating systems and production units

Approximately two thirds of residential dwellings in Denmark are connected to district heating, according to Fig. 4. The ratio of single-family houses supplied by district heating in Denmark is also high compared to international examples [5]. Throughout the country, district heating is distributed to end users via approximately 30,000 km of trench length, totalling 60,000 km of pipes [68,70,71].

CHPs produced 67.7% of the total heat distributed in Denmark in 2019. Heat-only generation plants provided the remaining 32.3% of the heat. Centralised CHPs accounted for 33% of the district heating and decentralised CHPs accounted for 15.1%. CHPs with secondary producers - for example, CHPs at waste treatment plants, industrial production sites and nurseries accounted for 19.6% of the district heating supply [69]. There are approximately 600 heat producing companies in Denmark and approximately 400 district heating companies. Some of these generate heat themselves, while others buy heat from external producers [68,69].

The large-scale centralised CHPs are located in the higher-density supply areas, that is, in urban or suburban areas [72]. They typically combine numerous production units, and they may comprise several heat distribution networks. The smaller scale decentralised CHPs and district heating production units typically serve low-density supply areas, that is, smaller cities and villages in more rural areas. The smallest district heating systems may consist of just one district heating distribution network and one base load unit, perhaps supplemented by one or more reserve units, commonly used only during the coldest weeks or months of the year. Peak- and reserve-load boilers are typically fuelled by natural gas or oil, as the initial investment cost for these supply units is relatively low. District heating in-house appliances vary throughout the country [68,71,72].

The energy supply for district heating in Denmark comprises natural gas, biomass, household and other waste, waste heat from industry, coal (in CHPs only), oil, thermal solar collectors, electricity and wind power via heat pumps, biogas and biomass [68,69]. CHPs powered primarily by coal supplied 8% of the district heating in 2019, while CHPs powered primarily by natural gas (5.7%), household- and other waste (22.7%) and biomass (29.8%) accounted for the rest. Taken by their primary fuel use, heat-only plants powered mainly by biomass accounted for 15.7% of the heat supplied in 2019, and those powered mainly by natural gas accounted for 7.8% of the heat supply. The market share for district heating in buildings is 56%, while the market share for fossil fuels is 19%, according to Fig. 3. A little over 20% of the residential buildings in Denmark rely on fossil fuel boilers for heating (oil or natural gas), while heat pumps, electric heating and biomass boilers account for approximately 3–4% each (see Fig. 4) [69].

5.2. Price and ownership models

The price of district heating varies from company to company. In 2019, the weighted average cost was 13,067 DKK annually for heating what is defined as an average household[3] – corresponding to 722 DKK/MWh or 97 euro/MWh. These annual costs include a Value Added Tax (VAT) of 25%. The average price of heat is almost the same for everyone, independent of heat density in the heat supply area; in other words, the price of heat is only slightly higher in single-family houses than in multi-family buildings or apartment blocks within each district heating network. Consequently, this basic pricing comprises cross-subsidisation for heat delivered to single-family houses, as the heat distribution costs and the heat losses are considerably higher in the lower density heat supply areas with single-family houses.

The average price of district heating for the end user has decreased in

[3] Here, an average household is defined as 130 square meters, and with an annual heat consumption of 18.1 MWh [75].

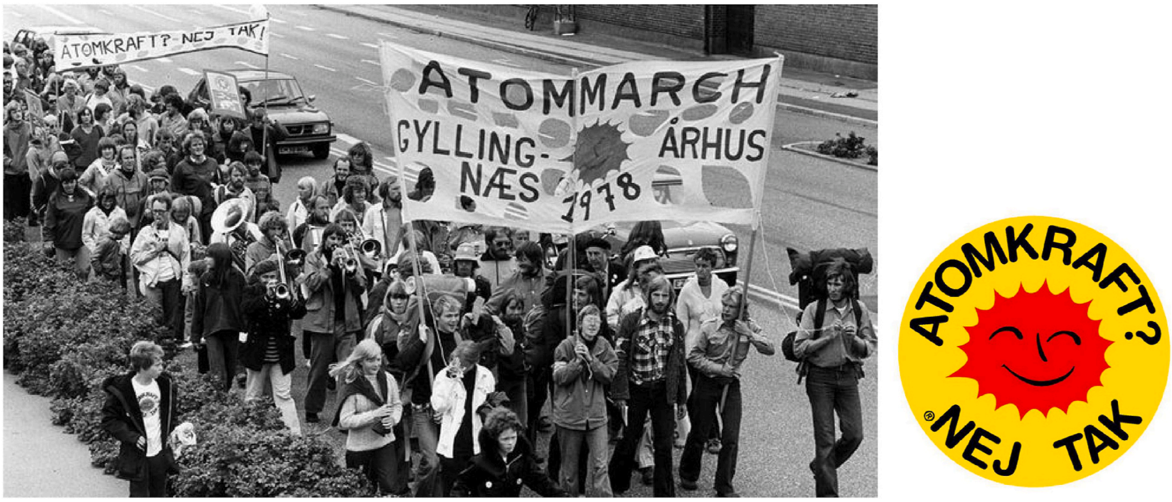

Fig. 5. Left. Antinuclear protest march, from Gyllingnæs to Aarhus, 1978. Right: 'Nuclear? No Thanks' Sticker designed for the antinuclear campaign. Reprinted with permission. Copyright: © ooa-arkiver.

recent years. In 2019, 15 companies charged more than 20,000 DKK annually for heating an average household, while 53 companies charged more than this amount in 2014. In 2019, 29 district heating companies charged less than 10,000 DKK annually for heating an average household, while only 13 companies charged less than this amount in 2014. A small price increase in 2019 was mostly due to the expiry of state subsidies for the bare field plants (see section 4.3) and price fluctuations in the electricity market [70]. The average price of district heating in Denmark is the highest national average in Europe [73].

There are two main ownership models for district heating in Denmark: cooperative ownership (typically AMBA, cooperatives with limited responsibilities) and municipal ownership (typically A/S, limited company, or I·S, general partnership). There are currently 49 municipally owned district heating companies. These are typically located in the more urban areas and are larger in scale. In 2019, municipally owned district heating companies supplied approximately 60% of the heat sold in Denmark. There are currently 323 cooperatively owned district heating companies. These are typically located in the more rural areas and are smaller in scale. In 2019, cooperatively owned district heating companies supplied approximately 34% of the heat sold. District heating companies with other types of ownership, such as private, accounted for 7% [68,74,75].

5.3. District heating and low-carbon energy transitions

The Danish district heating sector has integrated large amounts of renewable energy resources into the district heating systems within a relatively short time. The ratio of renewable energy resources in CHPs increased from approximately 20% in 1990 to 63.8% in 2019, and the ratio of coal used in CHPs decreased from approximately 50% in 1990 to 8.6% in 2019. This low-carbon transition is mostly via biomass, but also due to some thermal solar collectors and the recycling of waste heat from industry [69,70]. As growing proportions of renewable energy resources were integrated into the Danish district heating systems throughout the decades, the carbon emissions decreased accordingly (see Fig. 7, Fig. 8, Fig. 9 and Fig. 10).

From the outset, biofuels were framed as a temporary tax-free alternative to fossil fuels. No closure or end date for this economic incentive was set, however, and no viable alternatives emerged. With incredible flexibility and speed, many heat generation plants transitioned to bio-mass, and the demand for bio-mass far outgrew the nationally available resources. Biomass is currently imported to Denmark from various European countries, including Russia and North and South America [77,78]. Waste has also been imported to Denmark for heat generation for approximately ten years (see Fig. 9).

On average, carbon emissions have also decreased in EU district heating systems, with a 39% reduction compared to 1990 levels. Compared to the EU average, however, carbon emissions in Danish district heating systems are much lower, with a 65% reduction compared to 1990 levels (see Fig. 10). With the rather moderate EU ambition of reducing carbon emissions by only 20% by 2020 compared to 1990 levels, the carbon emission reduction rates in Danish and European district heating systems more than reached the stated EU goals. Natural gas is the predominant energy supply for heating in most European buildings, and heating from natural gas releases approximately 66 g of carbon dioxide per megajoule of heat generated. In 2017, specific carbon emissions from Danish district heating systems were almost 80% lower than heat supplied by natural gas systems (see Fig. 10).

5.4. The legal framework and heat infrastructure planning

This section outlines key heat-planning principles and practices from the Heat Supply Act (HSA) and the Executive Order for Approval of Collective Heat-Supply Infrastructures [79–81] on the principles for heat supply project approvals, financing and heat pricing.

Local city councils are currently the relevant heat planning authorities, and thus responsible for approving new heat supply infrastructure projects. The executive order for collective heat supply projects comprises the ministerial criteria for municipal heat supply infrastructure planning and related administrative practices. It also determines the criteria for approval of collective heat infrastructure projects by the local councils.

Local councils are obliged to assess the short-term, long-term, direct and indirect impacts of proposed municipal collective heat infrastructure projects through a process that leads to project approval or dismissal. This process calls for assessing the socio-economic impacts of the proposed heat supply project, the environmental impact, the contribution to ongoing low-carbon energy transitions, any possible alternative uses of the energy resources, cogeneration of electricity and heat, security of supplies for municipal citizens, the use of already existing heat supply infrastructures, job creation, and more [63,66,79].

Large-scale collective underground heat infrastructure projects are expensive, and therefore only viable given a) favourable financing and b) minimisation of the investment risks involved.

Historically, Danish heat supply infrastructure projects were typically financed via extremely long-term (i.e., 20–50 years) and favourable loansoffered via the Municipal Credit Bank [44], a credit bank owned by the Danish municipalities [82,83]. Investment risks were

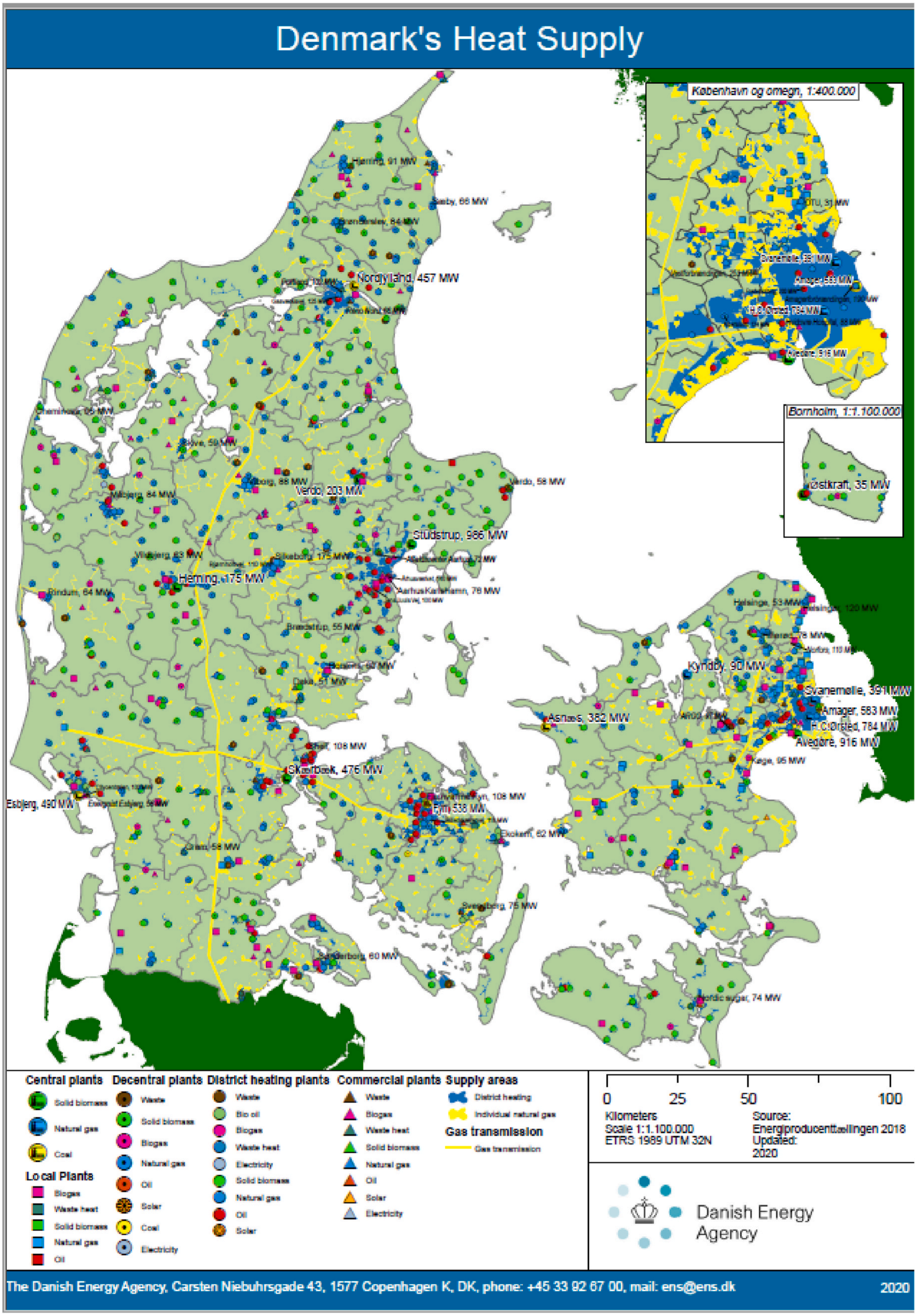

Fig. 6. Heat supply infrastructures in Denmark, 2020. Picture source: [6]. Reprinted with permission.

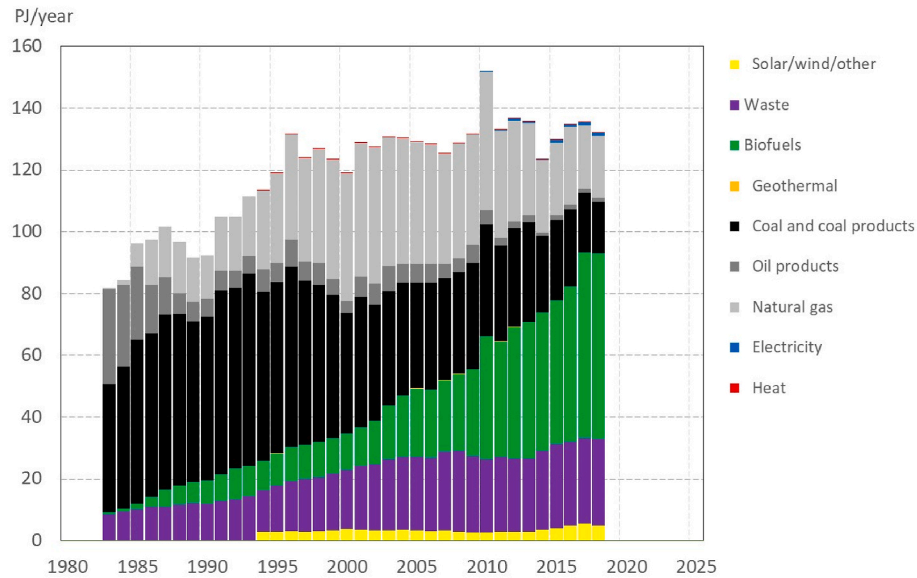

Fig. 7. Annual heat generation in the Danish district heating systems from 1983 to 2018 according to the original primary energy resources. Data source [76].

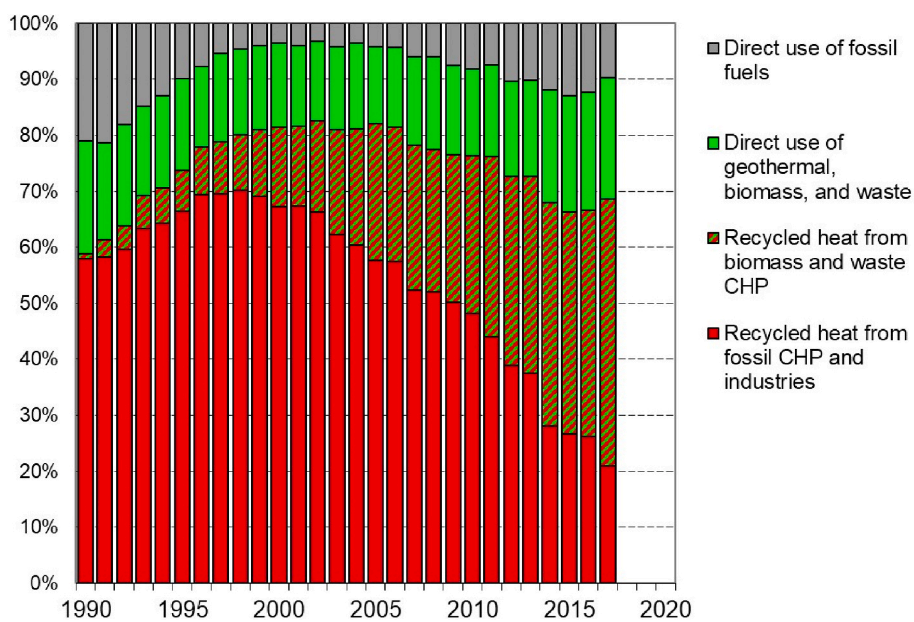

Fig. 8. Proportions of annual heat generation in Danish district heating systems from 1990 to 2017 according to four heat-supply method groups that reflect CHP and heat only plants together with fossil and non-fossil resources. Data source [76].

reduced via the 'mandatory connection' to collective heat supply infrastructures. The mandatory connection allowed municipalities to enforce a district heating subscription fee (but not district heating use) on municipal citizens in parts of or in all of the municipality. This guaranteed a minimum of heat sales/subscribers to the collective heat infrastructures. The mandatory connection was recently relaxed.

The final price of district heating is determined by and subject to the 'non-profit principle' / the principle of necessary costs. The non-profit principle holds that the final price of heating for the end user comprises the total and cumulated costs of providing heat service. In other words, the end user pays for heat generation infrastructure (capacity/effect), the total cost of fuels and fuel transport, heat distribution networks and storage facilities, investments, maintenance, operations and management, service, workspace and offices, and legal advice and consulting [66,72]. The non-profit principle is defined according to two basic principles of municipal law: the end users/consumers must not be subject to indirect taxation *or* to subsidisation via utility services. In other words, neither municipalities nor municipal citizens may profit from utility services [72]. In this way, the final price of district heating for the end user is kept low via the combination of favourable financing schemes on non-commercial terms, the mandatory connection, and the non-profit principle or the principle of necessary costs.

5.5. Institutional context: sector organisation and international collaboration

This section describes the institutional context and the organisational integration of the Danish district heating sector. It also shows that the Danish district heating sector is well organised and explores how sector organisations systematically facilitate international collaboration and outreach.

The government bodies primarily responsible for the Danish district

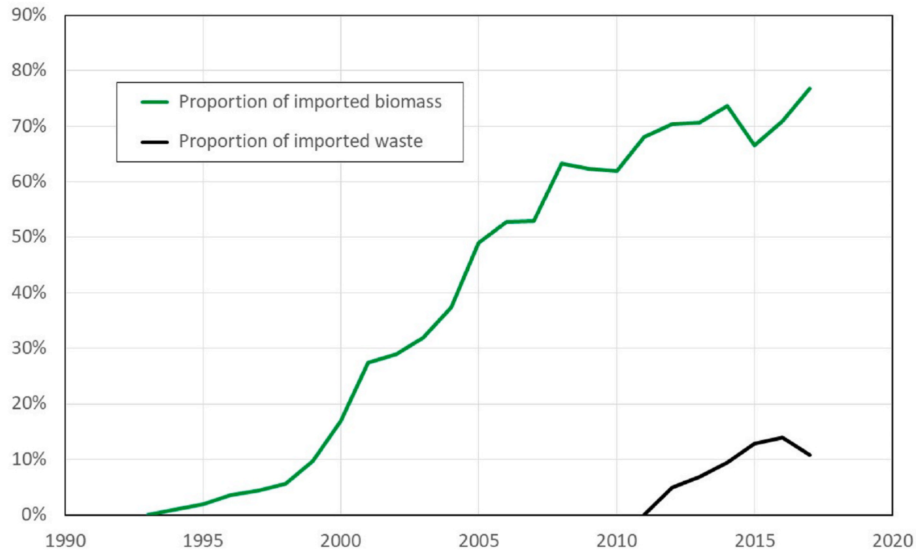

Fig. 9. Proportions of imported biomass and waste compared to all biomass and waste use within the Danish energy sector from 1993 to 2017. Data source [76].

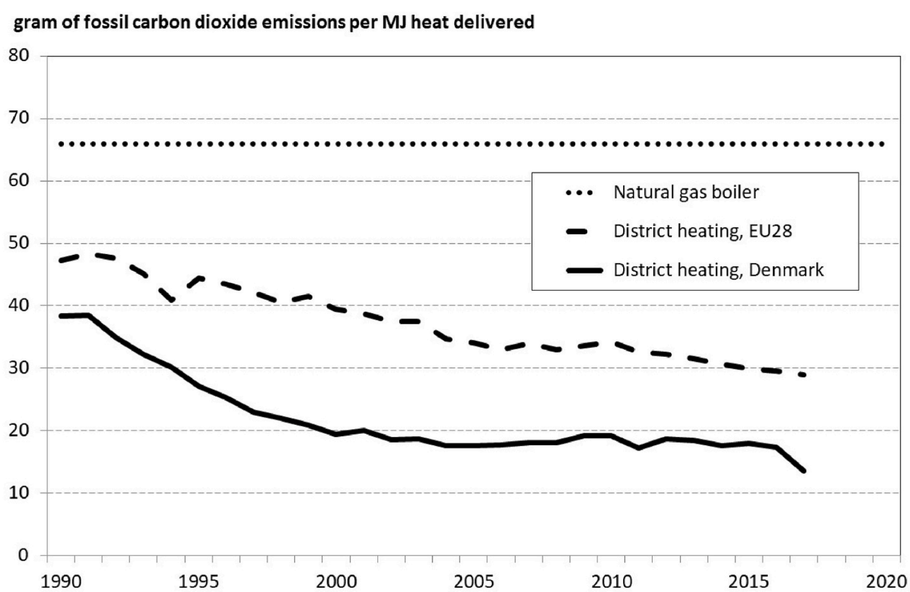

Fig. 10. Estimated average specific carbon dioxide emissions from 1990 to 2017 from the Danish and EU28 district heating systems compared to the corresponding emissions from natural gas boilers. An exergy-based allocation principle was applied for CHP according to Ref. [5]. Data source [76].

heating sector are the Ministry of Climate, Energy and Utilities and the Danish Energy Agency (DEA). The DEA is responsible for tasks related to the conversion and distribution of energy, and also for the ongoing process of low-carbon energy transitions in the Danish energy system [74]. Established in 2018, the Danish Utility Regulator (DUR) supervises the district heating, electricity and natural gas sectors. The purpose of the DUR is to secure consumer interests. This involves promoting efficient, stable, affordable and low-carbon utility services for all; promoting sector transparency, policy stability, innovative freedom, benchmarking and price regulation, as well as monitoring and developing the relevant legal frameworks in agreement with EU regulations [74]. As this list implies, shorter-term and individual consumer interests may not always comply directly with longer-term societal and environmental interests. Heat and energy price statistics are publicly available via the DUR [72,74].

The Danish government pro-actively exports the fundamental idea of district heating [1,5] via the government programme Global Cooperation. First and foremost, Global Cooperation supports energy planning and energy policy design in partner countries, the ultimate goal being to facilitate 'green growth' and to reach the Paris Agreement climate goals. District heating related initiatives comprise a substantial part of this programme [84,85]. Paraphrasing the Chinese model of 'panda diplomacy', some district heating sector professionals refer to these district heating initiatives as 'Danish district heating diplomacy'.

The Danish district heating companies are organised into two district heating associations: the Danish District Heating Association (DHA, 370 members[4]) and the Association of Danish CHP plants (ACHP, 70 members[5]). According to the DHA itself, the organisation supports member and consumer interests, while taking into account environmental

[4] In Danish: Dansk Fjernvarme. Homepage: danskfjernvarme.dk.

[5] In Danish: Foreningen Decentral Energy. In October 2020, the name of this organisation was changed to Foreningen Decentral Energy from the original name, Foreningen Danske Kraftvarmeværker. Homepage: fdkv.dk.

concerns, energy efficiency, stability of supplies and socioeconomic concerns [71]. The DHA annual general meetings gather approximately 2000 participants, and the relevant minister or other government representatives are often invited as speakers. The international manager of DHA has been active on the board of Euroheat & Power[6] for many years and is currently acting as its president.

The Danish Board of District Heating (DBDH), a privately funded organisation, supports Danish district heating interests. DBDH facilitates the dissemination of district heating-related information dissemination, international networking, knowledge sharing, and district heating related export activities. DBDH also publishes the district energy magazine, HotCooL, read by subscribers all over the world [44].

Overall, the Danish district heating industry, sector consultants and other district heating related industry actors cooperate both nationally and internationally, and they benefit from the international collaboration and outreach from the Danish district heating organisations.

5.6. Market aspects

Danish companies that work with district heating and related technologies and know-how have achieved advantageous market positions globally, and the district heating sector is important for the Danish economy. For example, a Danish company (Kamstrup) currently holds approximately half the global market of heat meters, and Denmark is a market leader in prefabricated district heating pipes (Løgstør Rør/Logstor), prefabricated district heating substations (Danfoss and Grundfoss) and district heating consulting services (Ramboll and COWI).

The district heating industry contributed a total of 17.6 billion DKK to the Danish GDP in 2019 and thus accounted for approximately 0.8% of the total Danish GDP that year. Sector exports amounted to 7.6 billion DKK, the highest ever. Moreover, interviews with ten global district heating companies revealed that more than half of their exports go to district heating technology subsidiaries located outside of Denmark, the main markets being Germany, Sweden and China. These exports are worth approximately 2.5 billion DKK, but are not registered in the Danish statistics [70]. In 2019, the Danish district heating and related sectors created 22,300 full time jobs. Approximately 7,500 of these jobs were within the district heating sector. 1,800 jobs were with the district heating companies directly, and approximately 900 people worked as consulting engineers. The turnover in the Danish district heating sector has increased by 7% since 2012 [70].

6. The future

6.1. District heating innovations

From the outset, the Danish district heating sector has been a forerunner within the global district heating industry. Several Danish manufacturers developed and improved the district heating pipe technologies in the 1970s and 1980s, achieving market leading positions in Europe. Ultimately, these developments led to the initiation of a Danish thermal engineering cluster of district heating providers, equipment manufacturers and consulting engineers, leading to further technical and organisational advances. Eventually, this cluster facilitated national exports of district heating equipment manufactured in Denmark.

Historical forerunners from the Danish district heating and related technologies sector are still innovating. For example, Logstor (founded in 1960) recently launched a district heating pipes manufactured using recycled plastics [86]. This suggests that, in the future, the recycling/harvest of otherwise wasted heat in district heating may also be facilitated by recycled district heating hardware/infrastructure. Moreover, heat control equipment provided by Danfoss (founded in 1933), and heat metering technologies and Artificial Intelligence (AI) solutions based on heat meter measurements from Kamstrup (founded in 1946), facilitate the optimisation of existing and older district heating systems and allow for increasing efficiency in future district heating systems.

Reaching the stated target of 100% decarbonisation of the Danish district heating systems by 2030 [71] involves ongoing integration of renewable energy resources, for example solar power and wind power, via large heat pumps and geothermal heating; large-scale and seasonal heat storage, and increased harvest of industrial waste heat.

In recent years, the solar collector capacity within Danish district heating has increased. Through the continuation of Swedish research from the 1980s, implementation of large-scale solar collector fields took off in the 1990s [87]. Currently, the largest solar thermal collector field in the world that feeds into a district heating system is located near the town of Silkeborg in Denmark. Inaugurated in 2016, this heat generation plant consists of 157,000 square metres of solar collectors with a 110-MW capacity [88]. Thermal performance and quality assessments are reported in Refs. [89,90]. As of 2020, more than 1.6 million square meters of solar thermal collector areas supply heat to about 120 small- and medium-sized district heating systems in Denmark, with a total installed capacity of 1,100 MW. The annual heat output is approximately 700 GWh, almost 2% of all heat input into Danish heating networks.

The heat pump capacity within the Danish district heating systems has increased in recent years, and experts expect this trend to continue as natural gas networks and coal are phased out [8,68,70,91]. Large heat pumps can utilise low-temperature heat in sewage and sea waters [92] and facilitate coupling of the energy sectors [91]. The potential of heat pumps is explored further in Ref. [93]. The installation of the first major heat pump (50 MW) in Esbjerg, Denmark, was announced in early 2021. This heat pump will use carbon dioxide as a refrigerant [94].

Geothermal heat obtained from large underground aquifers is currently only available at three Danish locations (Thisted, Sönderborg, and Amager). Geothermal heat has been identified as a future option in many Danish cities, although some geothermal projects have failed. The potential for further exploitation of geothermal heating is explored by Ref. [95].

Multiple methods and combinations of short-term and long-term storage solutions are pivotal for district heating systems. Particularly in the context of low-carbon energy transition processes, the integration of renewables, and sector coupling/energy systems integration, the potential for energy storage via the district heating systems is far from realised [2,91,96]. In conjunction with solar district heating systems, five large seasonal heat pit storage solutions were installed [97]. Corresponding to 10 GWh of heat, and with a water volume of 200,000 cubic metres, what is currently the largest heat pit storage solution in the world is located in Vojens, Denmark.

The harvest of industrial waste heat for domestic heating purposes is 100% heat recycling, and thus increases energy efficiency accordingly. For some years, however, Danish taxation hampered the harvest of waste heat. The relevant legal framework has recently been modified, and more harvesting of industrial heat that would otherwise be wasted will be possible in the future [98]. The potential for further exploitation of industrial waste heat is explored by Ref. [99]. In 2020, heat recovery from the newly established Facebook data centre in Odense went into operation [100]. In the future, waste heat from concentrated electricity use in new Danish data centres will become important heat assets.

6.2. Academic district heating research: energy scenarios and research hubs

In the last two decades, academic researchers have become more involved in district heating research. The two 'Heat Roadmap Denmark' energy planning research projects (2008 and 2010) were carried out at Aalborg University (Denmark) in collaboration with a consulting company. These projects comprised decarbonisation scenarios and low-carbon energy transition action plans for 2030 and 2050 [101,102]. In

[6] Also known as the European Association for District Heating and Cooling.

collaboration with other universities and district heating stakeholders, Aalborg University also initiated and coordinated the so-called Fourth Generation District Heating research project (4GDH) between 2012 and 2018. In defining 4GDH, this research project produced the currently most cited paper in the world about district heating (see Ref. [103]) according to the Scopus database.

Aalborg University later became one of the two founding universities of the Heat Roadmap Europe projects in 2012, carried out in collaboration with other district heating interest organisations and research hubs in Europe. The purpose was to explore how the European heating sector could be decarbonised at the lowest possible cost. One of the most important research outputs was the Pan-European Thermal Atlas, providing detailed information about European heat demand and future heat supply possibilities (see Ref. [104]).

According to a scenario analysis within Heat Roadmap Europe of the future EU heat demand, the greenhouse gas reduction ambitions of 80% by 2050 compared to 1990 levels can be achieved via the large-scale integration of district heating and district cooling [105]. The reference case, the Energy Roadmap 2050 [106], presented six alternative scenarios that focused on the electrification of the heat sector (e.g., via heat pumps) and electricity savings. In comparison, the scenario that involved large-scale district heating would reach the greenhouse gas reduction target and reduce the annual costs of heating by approximately 15% (corresponding to 100 billion euros) by 2050.

7. Discussion

Drawing upon the above introduction to the rich Danish district heating history and the outline of the diverse Danish district heating sector (see Fig. 6), this section touches upon key dilemmas, challenges and potentials faced within the Danish district heating sector. It discusses 1) the balance of fuel imports and exports and 2) the future role of WtEs in the district heating system, and it explores 3) future challenges and potentials for the Danish district heating sector overall.

7.1. From import dependency (oil) to import dependency (biomass)

In the race towards low-carbon energy transitions, the Danish district heating sector has transitioned to a high ratio of biomass within a relatively short time, and the sector is known for its integration of WtE plants into the energy system. While this emphasises the technical diversity, flexibility and *adaptability* of district heating systems, the balance of national fuel imports and exports has not proved straightforward.

Denmark and Sweden both stand out within the EU in that all of the heat from their WtE plants is utilised for electricity generation and district heating [107]. Danish policy now calls for more recycling, less waste incineration, less international waste imports, and more thinking in terms of a circular economy [108]. Some Danish WtE Plants may face future decommissioning, and the waste imports for Danish WtE Plants have been intensely debated [109,110]. As demanded by the current EU standards for the incineration of waste, Denmark currently hosts highly energy-efficient and high-tech waste incineration plants. On this more global scale, then: does it make sense to reduce international waste imports from, for example, countries that currently use landfills and sub-optimal, perhaps even toxic, waste incineration methods?

The main strategy for the decarbonisation of the district heating sector has been to substitute fossil fuels with biomass. This shows a combustion-based heat supply path dependency, and it has resulted in dependency on biomass imports (see Fig. 9). Moreover, stakeholders, NGOs and the media have recently (and rightly) questioned *how* sustainable the current volume of biomass imports may be, given the ratio of biomass imports / population size in the small country. They have also questioned the sustainability of biomass supplies from specific locations, such as South America [78,111]. The current Minister of Climate, Energy and Utilities still holds that biomass is but a temporary solution, and recently he touched upon taxing biomass to incentivize its reduced use [112]. Paradoxically, then, from the historical policy ambition of reduced fuel import dependency, to the policy focus on carbon reductions, the carbon reduction strategy in the Danish district heating sector has led to fuel import dependency once again. This time, the fuel dependency is on biomass. Moreover, in the pursuit of sustainability, this strategy has also resulted in the use of biomass/fuel sources from suppliers with sometimes rather dubious degrees of sustainability in the production chain.

A future challenge for the Danish district heating sector will be to balance this biomass import dependency with other heat supplies from non-combustion heat generation, for example wind power via heat pumps. The above dilemmas emphasize regional and global interlinkages and trajectories in terms of fuel use-, supply- and demand.

7.2. Future challenges and potentials for the Danish district heating sector

The Danish energy system is currently undergoing significant changes, most notably the integration of more intermittent renewable energy resources (mostly wind power), electrification and sector coupling.

As a result, the role of CHPs for electricity generation has is, and the historical Danish energy-planning strategy of integrating a large ratio of CHPs into the energy system challenged. In the future, the role of non-combustion heat generation will increase, mostly via, for example, implementing heat pumps and solar thermal collectors into the energy system, but also via further recycling of waste heat from industrial production. In low-density district heating supply areas, individual heat pumps as alternatives to district heating will become increasingly viable and attractive. For district heating providers, a future challenge will be to accept the ongoing transition from combustion to non-combustion heat generation, and from district heating to individual heat pumps.

In the future, 4GDH and 'smart' thermal grids will become fundamental to the ongoing energy sector coupling processes as more renewable energy resources are integrated into the energy system [103]. Denmark is well prepared for this challenge, since several 4GDH national research projects have been carried out in the country in recent years. Notably, as more countries engage in low-carbon energy transition processes, the importance of Danish district heating and related technologies and know-how may increase. In exporting these, Denmark could profit from their role as a major contributor to global decarbonisation processes.

8. Conclusions

Throughout the history of district heating in Denmark, the strategic integration of CHPs into the energy system and the recycling of waste-heat from industry have increased energy efficiency in the Danish energy system. Collective historical experiences and culture and interchanging political and social rationales have all motivated bottom-up and top-down support for the district heating networks throughout urban and rural landscapes in Denmark.

The cooperative mind-set, welfare state values, the global energy crisis, the consequent national economic crisis, and growing environmental awareness and concern were all pivotal for this technological journey. Core motivational drivers were ambitions of energy efficiency, heat supply stability, energy independence, energy equity and sustainability.

The Danish district heating networks – and the Danish district heating sector – is known as unique compared to international examples in terms of heat-planning strategies, supply-area characteristics, technical solutions- and combinations, energy efficiency- and sustainability, ownership models and financing, and research and development.

First, (a) the district heating penetration rate throughout Denmark is among the highest in the world.District heating supply areas include high-density urban areas *and* low-density rural areas, and the ratio of single-family houses supplied by district heating is high. From the early days, (b) the strategic integration of CHPs and the harvest/recycling of otherwise wasted heat from industry has ensured energy efficiency in the Danish energy system. The 1997 ban on landfills also provided an impetus for more waste combustion in WtE plants. The Danish district heating sector has (c) transitioned to a relatively high ratio of renewable energy resources, most notably biomass, in a short time. Second, financing models and heat pricing regimes are unique to Danish district heating. (a) Long-term loans on non-commercial terms and the mandatory connection reduce investment risks. (b) The non-profit principle or the principle of necessary costs determines the price of heat, and the average price of heat is almost the same regardless of heat density in the supply area. The average price of Danish district heating is relatively high compared to European levels. Third, the Danish district heating sector itself stands out as a forerunner among international district heating communities. This is due partly (a) to the thermal engineering clusters of heat providers, manufacturers and consultants that ultimately lead to technical advances and national exports, and partly due to (b) the sector organisation and systematic facilitation of international collaboration and outreach.

Looking into the future, the Danish district heating sector faces both challenges and potentials. Core future challenges for the Danish district heating sector relate to decarbonisation of heat supplies, the increasing biomass import dependency, the changing role of CHPs due to electrification of the energy system, and the integration of non-combustion heat generation methods into the district heating systems. However, the Danish district heating sector also looks towards future potentials vis-à-vis national- and global low-carbon energy transition processes.

In the bigger picture, and looking beyond district heating and the energy system, issues related to power generation, fuel supplies and fuel use cannot be viewed as only local in nature. These have global trajectories and global ramifications, and thus implications for future generations.

Credit author statement

Katinka Johansen: Conceptualization; Funding acquisition; Methodology; Formal analysis; Visualization; Writing – original draft; Writing – review & editing. **Sven Werner**: Conceptualization; Formal analysis; Visualization; Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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