Book Chapter

A Brief History of District Heating and Combined Heat and Power in Denmark: Promoting Energy Efficiency, Fuel Diversification, and Energy Flexibility

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Abstract

The World Energy Council ranks the Danish energy system among best in the world judging by the energy trilemma criteria: energy security, energy equity, and sustainability. District heating (DH) and CHPs are pivotal for this ranking. This brief historical account illustrates how a mix of historical events, collective societal experiences, cultural and political values inform the Danish history of DH and CHPs. After the global energy crisis in the 1970s, public and political sentiment called for energy independence, alternatives to imported fuels, and alternatives to nuclear power. National-scale collective heat infrastructure planning initiatives targeted the energy policy objectives: energy independence, fuel diversification, and energy efficiency, and a political culture of broad coalition agreements made the necessary long-term planning possible. In the following decades, growing environmental awareness and concern called for renewable energy resources as alternatives to fossil fuels. Research considered the role of collective memories and temporal distance (i.e., time) for this sociotechnical journey; it notes the innovative thinking, re-use/re-cycling and energy efficiency focus that still characterize the Danish DH communities today, and it suggests that the intangible, yet reliable nature of heat could lead to the rebound effect in end-user heat-consumption behaviours. The methodological question of how, and to what extent, historical insights and lessons learnt may be translated across contexts is raised and discussed. Although sociotechnical trajectories may have granted the Danish energy system a head-start in the global race towards low-carbon energy transitions, perhaps the route was less direct

than popularly portrayed. The Danish DH sector currently faces challenges of growing biomass import dependency, but also the potentials of sector coupling and energy flexibility. Energy efficiency and energy flexibility potential may be harvested via DH and district cooling solutions in future 'smart' energy systems globally. Hopefully, insights and lessons learnt from this brief history of Danish DH and CHPs prove informative elsewhere.

Keywords

Energy Transition; Renewable Energy; District Heating; Combined Heat and Power; Review; Energy Policy

Introduction

The Danish energy system is ranked among the best in the world by the World Energy Council (WEC) accordingly to the energy trilemma index criteria: energy security, energy equity, and sustainability [1]. The small Scandinavian country of Denmark is well known for its innovative energy sector: for wind power, wind power technologies, and for wind power integration in the grid [2-6]. The lesser-known underground network of district heating pipes throughout rural and urban Danish landscapes are equally important for the top WEC ranking of the Danish energy system, however. In the Danish energy system, district heating and combined heat and power plants (CHPs) ensure energy efficiency, via the harvest of otherwise wasted heat, and the use of low-quality fuels. DH facilitates fuel diversification, the integration of renewable energy resources (e.g., wind and solar) into the grid, sector coupling and increased energy flexibility [7-11]. This all facilitates low-carbon energy transition processes [12] (see Figure 1).

The aboveground wind turbines and wind farms have been subject to intense social and political controversies throughout recent decades [2,13-15]. In comparison, the underground network of heat supply infrastructures have lived rather quiet and anonymous lives [16,17].

From the early days, the Danish district heating sector has been viewed as a frontrunner among the international district heating communities, and the national scale collective heat supply infrastructure planning processes are regarded as unique [18,19]. As a result of these historical heat infrastructure planning processes, district heating networks currently supply approximately two thirds of the domestic households in Denmark with heat. This district heating penetration rate is among the highest in the world [20,21].

Insights and lessons learnt/drawn from the Danish history of DH and CHPs may prove to be beneficial elsewhere, and increasingly so as other countries engage in low-carbon energy transition processes globally [7]. However, the unique history of district heating and large-scale collective heat infrastructure planning in Denmark is overlooked internationally [16]. In outlining the historical role and importance of district heating and the associated technologies for the Danish energy system, this paper provides a start towards filling that long-recognized gap in the literature.

This brief historical account highlights the role and importance of cooperative culture and experiences, bottom-up innovative drive, the growing welfare state, the global energy crisis in the 1970s [22,23], and the subsequent national-scale collective energy planning initiatives [24,25] for this unique socio-technical journey. The research also outlines how Danish energy policy priorities gradually integrated ambitions for low-carbon energy transitions as public and political environmental awareness and concern grew.

The research is guided by the following research questions: (1) *What key historical events informed the emergence and the evolution of the Danish district heating sector?* (2) *What core values and rationales motivated and underpinned the planning and deployment of district heating networks throughout Denmark?* (3) *Reflecting on these historical trajectories: what are some of the future sociotechnical challenges and potentials for the Danish district heating sector?*

In terms of research limitations, the longitudinal historical perspective taken here leads to the compromise of less in-depth historical and political detail.

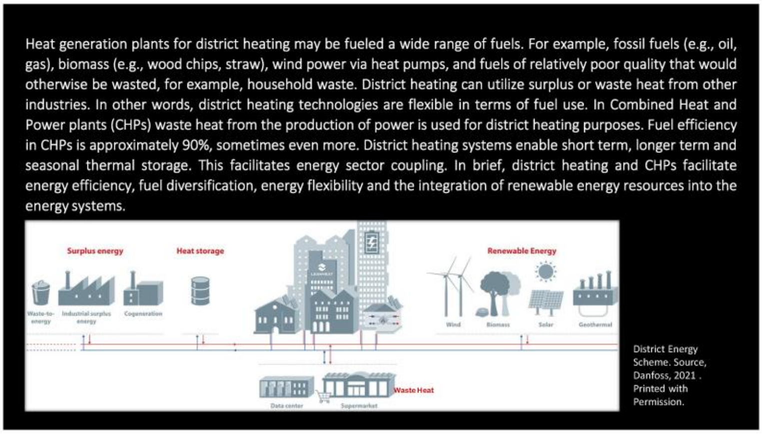

Figure 1: District energy/the integrated energy system. Sources [7,10,12,26].

Methodology

This research is conducted in the style of an integrative literature review [27]. For this purpose, the data that were collected from sector reports, legal documents, news, and sector websites supplement the academic literature on the subject matter. Importantly, integrative reviews welcome "experts as valid sources of evidence and as providers of continuous data collection and synthesis" [27]. For this research, more than 20 semi-structured interviews were conducted in 2019–2020 among district heating interest groups, sector consultants, legal experts, government experts, and district heating researchers. Informal interviews [28-30] were carried out while participating in district heating-related seminars, workshops, etc. Mixed methods research insights and data from the interdisciplinary research project InterHUB (see interhub.aau.dk) also provide important background information for the current study (These data include, for example, 1161 open-ended survey responses from a total of 175 respondents)

The longitudinal research perspective allows for rigorous critical assessment of the historical claims or beliefs held by stakeholders involved, and for exploring the long-term effects of decisions, plans, and rationales from the past [31,32]. Overall, this research draws upon and contributes to the interdisciplinary research domain that is Science and Technology Studies (STS) (see Table 1).

Table 1: Timeline: the first century of district heating in Denmark. This timeline shows key events that proved important for the Danish history of district heating. It notes key heat supply policy decisions, and important international reports and agreements.

1903	First waste incineration and DH plant in Denmark built in Frederiksberg; Provided heat and electricity for municipal institutions;
1914	1914–1918: WWI;
1920s	1920s–1930s: District heating systems infrastructures are developed;
1939	1939–1945: WWII;
1957	The Danish Association for District Heating is established;
1958	Nuclear power is considered as a future energy resource in Denmark;
1963	The book “Silent Spring”by Rachel Carson;
1962	Maersk awarded the right to investigate and exploit oil and natural gas resources in the Danish part of the North Sea; Danish Underground Consortium (DUC) established;
1968	Ministry report on the potential use of natural gas in Denmark;
1970	Swedish authorities permit construction of the nuclear power plant, Barsebäck, which is sited on the Swedish coast within proximity of Copenhagen;
1972	92% of the total national energy consumption is based on imported oil;
1973	1st International Energy Crisis;
1974	Ministry workgroup identifies 9 locations that are suitable for nuclear power plants in the western part of Denmark;
1976	The Danish Energy Agency (DEA) is established; The Danish Energy Plan 1976 prepares for long-term energy policy;
1979	2nd International Energy Crisis;
1979	Public protests against nuclear power;
1979	Danish Energy Policy;
1979	1st Heat Supply Act: Introduced domestic natural gas

	into the heat supply infrastructures via the planning concept of 'zoning' and ensured the use of waste heat from industry and from power generation via CHPs;
1980	54% of the heating is based on oil;
1981	1981–1982: National scale heat planning throughout the country. District heating and natural gas heat supply areas or zones are determined via the concept of zoning;
1984	Extraction of natural gas from the Danish part of the North Sea begins;
1985	Parliamentary decision: They voted no to nuclear power in the Danish energy system; Coal excluded from national heat planning;
1985	The price of oil drops; Energy taxes are increased to ensure the continued focus on energy efficiency;
1985	94% of the power generation in Denmark is based on coal imports;
1986	Nuclear disaster at Tjernobyl;
1986	The political co-generation agreement; Emphasis on small-scale CHPs;
1987	The Brundtland Report: Our Common Future;
1897	The biogas action plan. Aim: to develop competitive biogas plants
1990	Energy 2000: The first plan for low-carbon energy transitions in the world;
1990	2nd Heat Supply Act: New heat infrastructure planning system introduced, and it plans directives and guidelines for fuel choice and CHPs introduced for municipalities and local authorities;
1990	Specific prerequisites regarding fuel choice and co-generation sent to various municipalities;
1992	Subsidies introduced to support energy efficiency measures, CHPs, and renewable energy;
1992	United Nations Framework Convention on Climate Change, UNFCCC;
1993	Political agreement made on the use of biomass in power generation; Criteria set for the future use of biomass;
1997	The Koyoto Protocol implements objectives of the UNFCCC;
2000	3rd Heat Supply Act: Parliamentary decision to improve conditions for small- and medium-sized decentralized CHPs and bare field plants.

The Early Days

The 1900s—WWII: The First District Heating Plant in Denmark

The first district heating plant in Denmark was a primitive Waste-to-Energy (WtE) plant. It was inaugurated in Frederiksberg in 1903. Located outside of Copenhagen at the time, the municipality of Frederiksberg attracted workers from afar to the growing industrial sector, and the population grew rapidly. The land that was used for landfills was in short supply, and it was expensive. Without no landfills for waste disposal, growing mounds of household waste accumulate on the streets.

Inspired by a recent innovation in Hamburg, the authorities solved this problem with a primitive waste incineration plant that produced heat and electricity. The waste was collected in horse-drawn carriages, loaded into storage silos, and from there, it was sent to the incinerators. In the form of steam, the heat was then transported to a nearby municipal hospital, an orphanage, and a house for the poor via underground tunnels. Thus, the first district heating system in Denmark was born [22,33,34] (see Figure 2).

This first district heating system proved to be inspirational throughout Denmark. Most of the existing power plants at the time were built in the 1900s, and they were obliged to deliver both power and heating. In the 1920s, these power plants needed to be restored and modernized. In this process, many municipalities chose to construct primitive combined heat and power plants (CHPs), and they used excess heat from the production of power for heating, e.g., dwellings or institutions close by. These first systems were mostly small and located close to the end-users/consumers [22,34,35]. The fuel import dependency at the time also motivated the energy efficiency advantages of the CHPs [19]. From early on, the values and management practices of the Danish cooperative movement [36,37] found new footing within the growing energy sector [4,22]. Particularly in smaller provincial towns and villages, local cooperative initiative groups invested in and managed the district heating plants [4,22,36] (see Figure 2).

Figure 2: Top left: landfill and waste management challenges. Top right: sectional drawing of Aarhus incineration plant. Bottom: horse-drawn garbage wagon. Source: [38].

Post-WWII: The Emergent Welfare State, Cooperative Values, and Favorable Financing

Decreased fossil fuel imports during WWII led to an energy crisis in Denmark, and the German occupation of the country from the year 1940 effectively stopped further expansion of the district heating networks [4,34,39,40]. Fuel was in short supply, it was rationed, and heat-only boilers were established as backups at some CHP plants. After the war, it seemed rational to expand the existing heat supply infrastructures with this excess heat production capacity [4,33,34]. At the time, electricity production was mostly centralized. Coal was still the prioritized fuel, and therefore many of the newly established power plants were located by the coast, as this facilitated the transport of coal. The Danish Government commenced the import of hydropower from the neighboring country of Norway [23].

The human atrocities of the World Wars emphasized that technological Innovations could also unleash powers of mass destruction such as those of the atomic bombs, and the East–West divide scarred the post-war political landscape.

Fuel rationing lasted until 1953 [41-44]. In the 1950s and 1960s, the public sector grew. The Social Democrat, Viggo Kampmann (prime minister 1960–1962), formalized the notion of the Danish welfare state, and the government adopted legislation based on the social rights of citizens. Social welfare was equal for all, and this social welfare included all of the sectors of society [41]. In the rural and urban landscapes throughout Denmark, public schools, nursing homes, and other public institutions were established, and new residential areas emerged. The energy sector grew rapidly in the 1950s and 1960s, and the underground network of district heating infrastructures took in new territories [18,22,34].

Two main ownership models for district heating were predominant. (1) Cooperative ownership of district heating plants was the most common ownership model in the more rural areas, when local initiative groups jointly invested in local district heating plants (see Figure 3). (2) In the more densely populated urban areas, municipal ownership was the most common model. Municipalities typically invested in larger-scale centralized CHPs, and sometimes they did so in cross-municipal partnerships [42,43]. Some municipal power plants were CHPs, and others released the waste/excess heat from production of power into the ocean [22,34]. Favorable long-term loans (e.g., 20–50 years) for these large-scale expensive heat infrastructure projects were available via the Municipal Credit Bank [33,43] (see Figure 3).

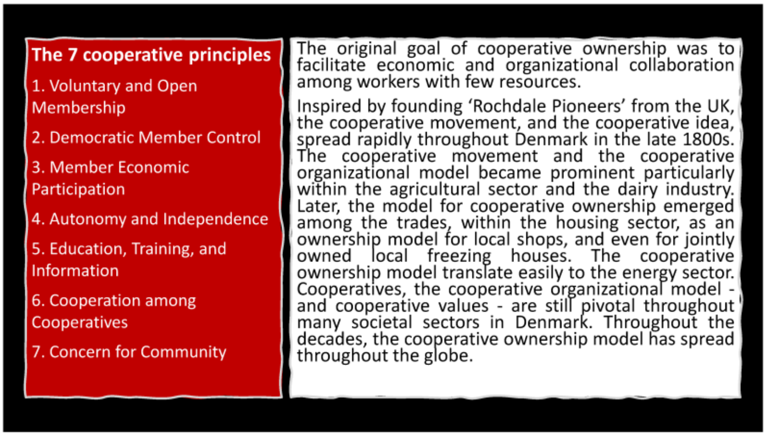

Figure 3: The 7 cooperative principles. Source: [36].

The 1960s: Economic Upswing, Technological Advances, and International Instability

The 1960s saw the Vietnam War and the Cuba Crisis, the assassination of President Kennedy, the Civil Rights Movement, and the Hippie Movement, the first man on the moon, the Beatles, Woodstock and Jimmie Hendrix, and the Anti-Nuclear Power Movements. In 1962, the book 'Silent Spring' by Rachel Carson documented the detrimental impact of the pesticide DDT on the ecosystem. Her meticulous research and poetic descriptions alarmed the world [40]. In the 1960s, A.P. Møller Mærsk (Maersk) was awarded the right to exploit any of the oil and natural gas reserves in the Danish part of the North Sea [23,39].

Economic upswing characterized the 1960s. In Denmark, the Danish welfare state continued to grow. Living standards improved, and consumption grew accordingly [22,23,39]. Oil was abundant and inexpensive. Oil was easy to transport and to handle. Oil was the prioritized fuel in this almost totally import-dependent country. The industry transitioned to the use of oil. The carpool grew. Oil burners were installed in residential housing, and the demand for oil grew. In 1967, the Six-Day War served as a brief reminder of the political unrest in the Middle East [6,22,39].

The future energy roadmap for the Danish energy system was not yet final in the 1960s. Nuclear power was still considered an option, and in 1966, the Nuclear Power Committee presented their report on potential nuclear power plant sites in Denmark [39]. Public opinion was largely against nuclear power, however [4,22]. In 1970, the Swedish authorities voted for the construction of the nuclear power plant, Barsebäck. Barsebäck was in operation by the mid-1970s, and it was visible from the Danish capital, Copenhagen, on a clear day.

In the early 1970s, approximately three quarters of the 500 Danish district heating plants were heat-only generation plants, and the rest of them were either CHPs or WtEs. Most of these were fueled by heavy oil [18,34]. The district heating technologies improved. Pipes and insulation technologies became more efficient, and low supply temperature district heating was introduced in some towns [34]. With these improvements, the popularity of district heating grew [45,46], (see Figure 4).

Figure 4: Deployment of 300 mm main pipes across the water in Aarhus, 1955. Source: Affaldvarme Aarhus; this was printed with permission.

As the populations grew, and as urbanization processes took off, the Danish suburbs also grew. The newly built suburbs were strategically planned, and were typically designed with district heating [39,46,47]. By the early 1970s, approximately one third of the Danish dwellings were supplied with district heating. This district heating penetration rate was among the highest in Europe [18].

In brief, the early days of district heating in Denmark were characterized by the cooperative culture, a bottom-up pragmatic approach to solving local heat-supply challenges, and the growing welfare state.

The International Energy Crisis

From Free Market to Energy Policies and Long-Term Energy Planning

In 1972, almost two thirds of the oil that was consumed globally was produced outside of Europe, the USA, and the USSR. The price of oil was low, and oil was readily available. At the time, Denmark was almost 100% dependent on energy imports. Ninety-two percent of the total energy consumption (TEC) in the country was based on the use of oil, and approximately ninety percent of this oil was imported from the Middle East [6,23,48-51]. The Government practised what has been described as a “lasseiz-faire policy and reliance of market forces” for ensuring the future stability of the fuel and energy supplies [38,39]. Thus, the international oil and energy crisis was a wake-up call for the Danish authorities: The price of oil quadrupled, and the household budgets for heating increased accordingly. The economy suffered, and unemployment soared [6,39,52-54]. The energy crisis had global ramifications, and the experts predicted a future shortage of energy and raw materials [40]. The Danish Government now set out to ensure that the national energy supplies would not be left to the dynamics of the free market in the future [4,39].

In 1972, the oil platform Dan field in the Danish North Sea produced the first oil. That same year, the commercial transmission company for natural gas (D.O.N.G. A/S, the company is now known as Ørsted/Orsted) was established. At the time, the Danish State was the only shareholder [23,40].

As a response to the global energy crisis, the Danish Government introduced short-term and long-term remedial measures to mitigate fuel shortage. Short-term remedial measures comprised lowering the speed limit in towns, no driving on Sundays (i.e., the so-called Sundays without cars, see Figure 5), encouraging the use of public transport, and incentives for reduce oil consumption within the transport sectors and in industry [23,39]. Colder indoor temperatures and cold showers became the norm. Throughout the Danish population, people felt the consequences of the energy crisis [23], and the Danish population was ready for change [23,46,49].

Figure 5: The energy crisis. Sundays without cars. Source: [55].

The Danish Government also commenced long-term strategic energy planning [56]. The Danish Energy Agency (DEA) and the Ministry of Energy were established to perform the job. Within public, academic, and political realms, energy-related questions, and future energy scenarios, were intensely discussed, and within the Danish Energy Agency itself, experts and energy professionals were split by their differing and ideologically weighted views of the future energy roadmap for Denmark.

By the late 1970s, anti-nuclear protests were common, and anti-nuclear sentiments were widespread among the Danish public. The anti-nuclear movements promoted the use of renewable energy resources (e.g., wind and solar) as alternatives to nuclear power (see Figure 6) [18,49,50]. In 1976, the energy planning priorities and policy principles for the Danish energy system going forward were finally published in the Danish Energy Plan 1976, see [56]. The main ambition of this plan was to reduce the energy import dependency of Denmark, thereby also reducing the associated economic vulnerability of the country [35,57-59].

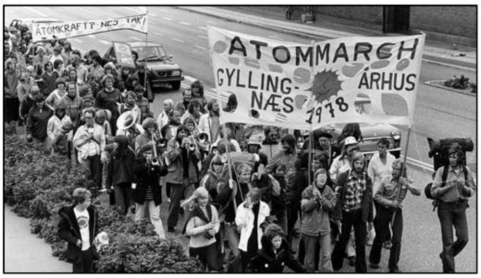

Figure 6: Left: public protest nuclear power. Right: the iconic “Nuclear Power? No Thanks” icon from the Danish anti-nuclear movement. Source: [55].

Danish Energy Policy: Energy Efficiency, Energy Independence, and Fuel Diversification

The 1976 Danish Energy Plan [56] focused on ensuring reliable energy supplies for Denmark going forward. To this end, the goals were: (I) reducing energy import dependency, (II) more diversification of fuels used, and (III) promoting energy efficiency and reducing the total amount of energy consumed nationally. This plan comprised plans for large-scale collectively heat infrastructures, the use of otherwise wasted heat from industry, integration of CHPs in the energy system, and the harvest of locally available renewable energy resources. To this end, the plan also boosted renewable energy technology research and development [56-59].

The 1979 first Heat supply Act (HSA) [see 57] supplied the legal framework for the heat planning initiatives ahead. The HSA supported the energy policy ambitions of (I) energy independence, (II) fuel diversification, and (III) energy efficiency. The HSA also called for (IV) integration of the newly discovered natural gas from the Danish North Sea into the Danish energy system. Tax revenues from the natural gas project supported the rapidly growing costs of the Danish welfare state [60-62]. The HSA also (V) prepared for the principal decision about nuclear power in the Danish energy system [39,57,59].

The heat infrastructure planning initiatives ahead targeted: A 53% market share of district heating by the year 2000 compared to the 1981 base of approximately 43%, a market share of Danish North Sea natural gas of 16% by the year 2000 compared to the 1981 base of 2%, and a reduction in domestic oil burners to 18% by the year 2000 compared to the 1981 base of 51% [9,39,63,64]. The Danish Government introduced 20% subsidies for renewable energy technologies [39,59], and deliberately worked towards broad political coalition agreements to ensure that the necessary long-term energy planning could be carried out. This political tradition (or culture) of broad political coalition agreements is still predominant today [59,61,62].

In 1985, the public and political debate about the integration of nuclear power in the Danish energy system was finally over. The Danish Government voted against nuclear power. Plans were also made to phase out the use of coal [39,59]. In April 1986, the nuclear disaster in Chernobyl, Ukraine, shocked the world [39,40].

National Scale Heat Supply Infrastructure Planning

The large-scale heat planning initiatives set out by the HSA involved a process referred to as 'zoning' (see Figure 7). The purpose of zoning was to (a) define the geographical zones or boundaries for the natural gas networks and the district heating networks, and by doing so also ensuring (b) the most efficient heat supplies in the cities and other urban areas. This process involved assessing and comparing the costs of the natural gas networks, the district heating networks, and the individual household oil boilers. The zoning process also ensured that (c) heat from the larger CHPs and waste incinerators supplied the local district heating systems via transmission systems [25,64,65].

The heat infrastructure planning activities took place throughout Denmark in April 1981. Municipalities who had not yet completed the task by the given deadline were instructed to do so promptly [39]. Experts involved in the heat planning initiatives at the time recall the process as being characterized by vibrant enthusiasm, and by the belief that these heat planning initiatives would bring about widespread social and environmental benefits.

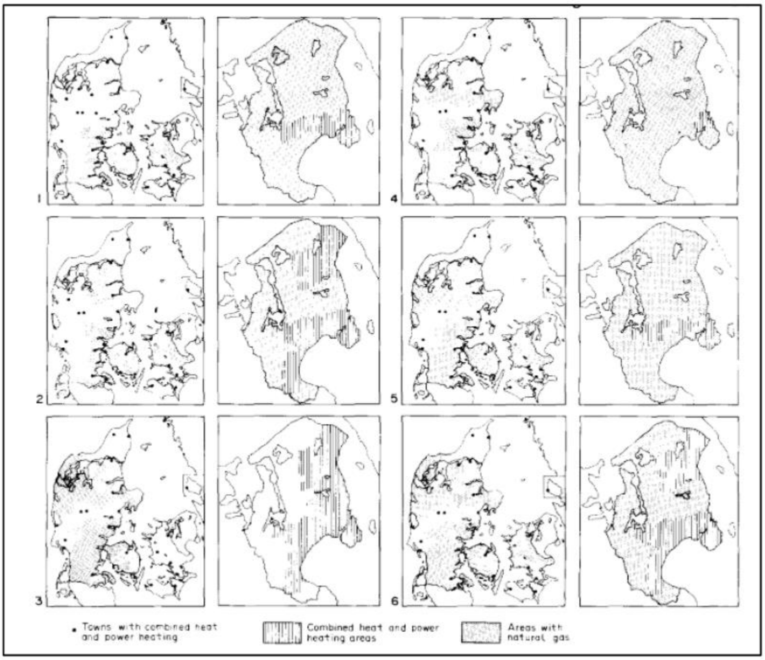

Figure 7: Proposals for regionalization/zoning of heat supply by type of heat supply system. Source: [25]. Notes: The process of zoning comprised three independent stages: (1) Individual municipalities mapped their heat demands, heat supply sources, fuel usage, and assessed future changes in heat demand/heat supplies. The municipalities then sent this information to the regional authorities. The regional authorities were responsible for producing a regional-scale overview of the heat supplies. Based on this regional overview, (2) the municipalities created preliminary plans for their future heat supplies. The counties summarized these plans at the regional level. (3) The counties then developed regional-scale plans for their future heat supply infrastructures [25,59,64].

The purpose of the zoning processes was to prevent over-investment in the expensive underground heat infrastructures, and to prevent internal competition between the collectively planned heat supply infrastructures for DH and natural gas [25,59,64].

The 1980s: Danish North Sea Oil, Natural Gas, and the Question of Nuclear Power

The 1980s saw the first mobile phones, the emergence of the World Wide Web, more relaxed East–West relations, and the fall of the Berlin Wall. The 1980s also saw explosive population growth, the Ethiopian famine, spread of the AIDs epidemic, and the Bhopal disaster in India [40]. Scientists began discussing phenomena such as global warming, the greenhouse effect, the 6th mass extinction, and the age of the Anthropocene [66]. In 1987, the Brundtland Report introduced the concept of ‘sustainable development’ for the first time [67]. That year, only 17% of the Danish population even considered the importance of reducing energy consumption according to the Danish opinion polls [39].

In 1980, American experts estimated that the oil and gas reserves in the Danish part of the North Sea could lead to energy independence in Denmark, and perhaps for as long as 20 years. That same year, activist groups argued that the rights to these natural resources should belong to the Danish State, and not to the Danish Underground Consortium (DUC) and the private entrepreneur, A.P. Møller Mærsk [38,39]. The Danish Government initiated negotiations with the DUC about the return of these resources to the Danish State, but after 294 days, the parties were no closer to an agreement [39]. The subsequent negotiations *did* result in stricter concession terms, however. The State demanded the more rapid production of oil and gas, and it secured rights to 40% of these. The Danish North Sea oil and gas organization generated revenue for the first time in 1988 [23,39,68].

The Danish economy was not performing well by the mid-1980s, and the Government introduced restrictive fiscal policies. The economy of the natural gas project was also poor, and a 1984 political coalition agreement ensured political support for the use of—and the further integration of—natural gas in the national heat supply infrastructures [9,39]. The 1986 political co-generation agreement prioritized the co-generation of heat and electricity (CHPs), and the state-owned electricity companies were told to establish a total of 450 MW smaller scale decentralized CHPs that were fueled by natural gas. Test- and demonstration projects for experimenting with the use of, e.g., waste, biomass, and biogas, were also included in this political agreement [39,59,69]. To ensure sufficient natural gas supplies, in 1989, the State and D.O.N.G. A/S signed a natural gas contract with the Danish Underground Consortium (DUC) which lasted from 1989 to 2012 [39,69,70].

Danish engineers improved the district heating pipe technologies substantially between the 1970s and 1980s. These products became important international exports, and a Danish thermal engineering knowledge hub of the district heating providers, equipment manufacturers, and consulting engineers was established [68]. In the late 1980s, electric heating was banned nationally in newly established housing in the natural gas or district heating zones [9,35,39]. Despite minimizing the competition from alternative heat supply sources, the economy of the collectively planned natural gas heat supply infrastructures was still poor. The experts suggested introducing a so-called 'mandatory connection' to the collectively planned heat supply infrastructures. The experts also suggested that some of the selected power plants should use surplus natural gas instead of coal [9,39,59] (see Table 1 and Table 2). For an overview of the relevant legislation and historical commentary, see [71-75].

Growing Environmental Awareness and Concern

The 1990s: Low-Carbon Energy Transitions

By the 1990s, environmental awareness and concern were growing in Denmark and globally. The United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1992. The UNFCCC was based on the common understanding that the climate change was real, and that it was predominantly caused by humankind. The UNFCCC committed signatories to the reduction of greenhouse gas emissions. The

1997 Kyoto Protocol extended the objectives of the UNFCCC [9,39,66].

In Denmark, the heat-supply infrastructure planning and zoning processes that had been initiated in the 1980s were almost complete in 1990. Danish energy politics and environmental politics became intimately intertwined in the 1990s. 'Green growth' and sustainable development was the order of the day. In 1990, the Danish Government published the first plan for greenhouse gas reductions in the world: the Energy 2000 Action Plan. The Energy 2000 Action Plan targeted reduced energy consumption and reduced CO_2 emissions. To this end, it proposed a range of subsidies for energy efficiency measures, and for the integration of more renewable energy technologies (RETs) into the energy system. It recommended environmental taxes, updating of the building regulations, and more control of the heat-related infrastructures [39]. The Energy 2000 Action Plan also aimed to secure the economy of the national natural gas project [35,39,59].

To implement the objectives of the Energy 2000 Action plan from 1990, the Heat Supply Act (HSA) was revised that same year. The 1990 revision of the HSA [70] mandated the integration of more CHPs in the national heat supply infrastructures. It also called for increased integration of natural gas, biomass, and wind power in the energy system [39,59,76].

In the 1990 revision of the HSA, the heat supply infrastructure planning was decentralized, and heat supply infrastructure planning would be conducted on a project-to-project basis going forward. The purpose was to increase the local ownership of the municipal heat supply projects, and to facilitate the integration of local ideas and initiatives in municipal heat planning practices [59,70]. Local municipalities/municipal councils were now responsible for ensuring that the future heat supply infrastructure projects were carried out in accordance with the Ministerial criteria [24,70]. To minimize the investment-risks associated with the large-scale collective heat supply infrastructure projects, the Executive Order for 'the mandatory connection' to collective heat infrastructure was adopted [59,70] (see Table 2, Figure 8 and Figure 9).

Table 2: The three key legal principles from the Danish Heat Supply Act. Source: [59].

The Non-Profit Principle	In Denmark, district heating is subject to the *nonprofit principle*, sometimes also referred to as the *principle of necessary* costs. According to the non-profit principle, the final price of heating for the end-user reflects no more or no less than the total price of heat generation and heat distribution. In other words, the final prices of heating for the end-user comprises and reflects the cumulated and necessary costs of heat-production transmission and distribution, investments and operating depreciations, maintenance, management, legal advice, consulting, service, and so on. Revenues and expenses must balance throughout the years. Utilities cannot generate profit or debt from heat-sales, as this indirectly subsidizes or taxes the end-users. Heat prices for all Danish utilities are publicly available via the Danish Utility Regulator (DUR) homepage.
The Mandatory Connection	The ‘mandatory connection’ empowered municipalities to enforce subscription/connection to the collectively planned heat infrastructures in the municipality. For municipalities, the mandatory connection guaranteed a minimum of end-users/consumers to the heat distribution net, thus minimizing the economic risks involved with the long-term investments necessary to finance the expensive underground heat infrastructures. Thus, the mandatory connection ensured a healthy economy for heat infrastructure projects. Municipalities could choose to enforce the mandatory connection fully, partially, or not at all. Citizens subject to the mandatory connection were free to supplement their heating with other heat sources, but obliged to pay the annual subscription fees for collective heat infrastructures.
General & Specific Executive Orders	The Heat Supply Act (HSA) empowers the relevant Minister to regulate municipal heat planning via Executive Orders. These may be nation-wide (General Executive Orders), or they can apply for specific named geographical areas (Specific Executive Orders). General Executive Orders ensure that the local councils responsible meet the objectives of the HAS. They also ensure that the municipal administrative practices reflect those criteria. General Executive Orders determine the general criteria for fuel choices, heat planning/reconstruction deadlines/timeframes, co-production and stability of

	supplies. They also take into account socioeconomic and environmental issues, technical advances etc. Specific Executive Orders for heat planning determine criteria for local fuel choices, limitations to or boundaries between different types of heat supply, etc.

Specific Executive Orders for Co-Generation

In September 1990, the energy minister sent targeted Specific Executive Orders (see Table 2) to the local councils in the Danish municipalities. Some of these ordered for the reconstruction of named/specific local district heating plants to become decentralized CHPs fueled by natural gas, and others into biomass plants, by the year 1998 [39,75,77]. This ensured that the natural gas networks and district heating networks did not compete internally, but that they fed into separate heat supply areas. The Minister at the time, Poul Nielson, relaxed the language of these Specific Executive Orders, re-labeling them as ‘writings of precondition’ (In Danish: Forudsætningsskrivelser) [75]. Regardless of word choice, however, the named municipalities were obliged to follow the Ministerial instructions (see Table 2).

In the decentralized CHPs fueled by natural gas, the natural gas companies avoided the risks of a distribution network for natural gas. In the following years, 87 of these decentralized CHPs were dubbed ‘bare field plants’, a label suggestive of the relatively low housing density in the heat supply areas they served. Bare field plants typically served smaller towns or villages [59,75]. The label ‘bare field plants’ is not mentioned in the Heat Supply Act, but it is mentioned in the drafts and in the preparatory works [75].

At the time, the price of electricity was high, and the price of the natural gas was low. So, despite the acknowledged heat loss in the heat distribution networks throughout the low-density housing heat supply areas the bare field plants served, their economy was sensible from the outset. The price of gas increased unexpectedly, however, and the economy of many bare field plants suffered [17,59,75].

In 2000, a political majority voted for the economic support of these decentralized bare field DH plants and CHPs [39,75,77]. In order to do so, the Heat Supply Act was revised yet again [77]. More economic support was granted the bare field plants in the following years, and the natural gas companies supported the bare field plants economically too [17,59,75].

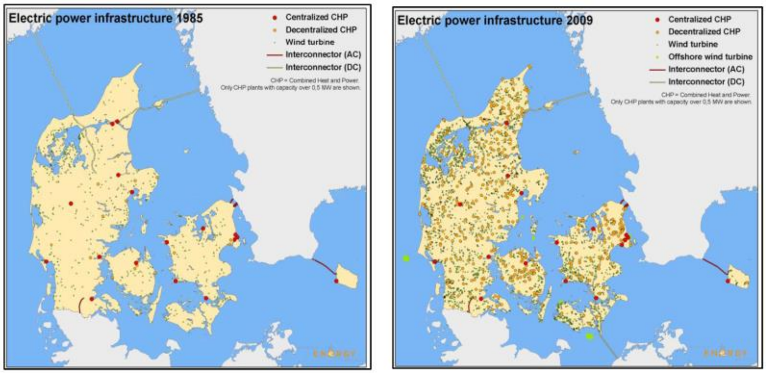

Figure 8: Centralized and decentralized CHPs in Denmark. Left: year 1985. Right: year 2009. Source: [69].

In 1997, the Danish Government adopted the first complete ban on landfills in the world [78]. In 1998, the previously energy import-dependent country of Denmark was finally energy self-sufficient due to the profitable Danish North Sea oil and gas [6,39].

Turn of the Century: New Challenges and Potentials for District Heating

The turn of the century was shadowed by 9/11 and the War on Terror. Environmental concerns grew, and climate change was increasingly accepted as a fact. The 2000s also saw the explosive growth of internet use, internet trade, and social media [40].

In 2001, Danish politics took a less environmental turn as a new right-wing government came into power. The responsibility for the energy sector was then moved from the Ministry of the Environment and Energy (1994–2001) to the Ministry of

Economy and Industry (2001–2005) [69,79]. Remarkably, the ambitious policy goals set out in the 1976 Energy Policy and the 1979 Heat Supply Act were more than achieved by the year 2000 [80] (see Figure 8 and Figure 9).

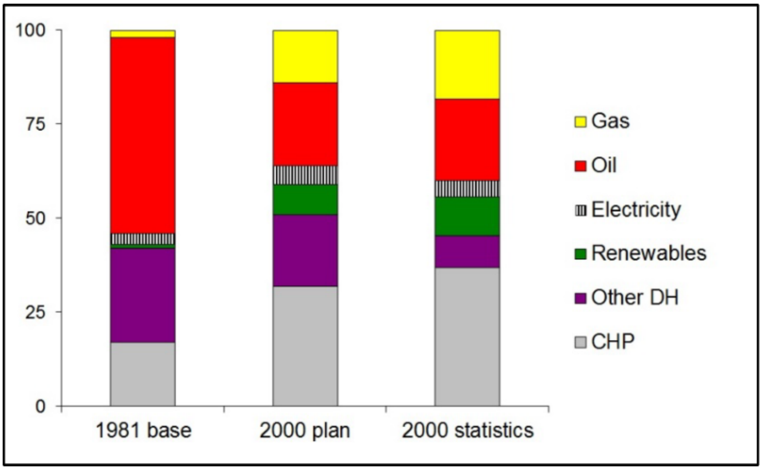

Figure 9: Heat sources in Danish households: Columns from left to right: 1. Year 1981 base. 2. Year 2000 model results made in the 1980s. 3. Year 2000 statistics. Source: [80].

Moving into the 21st century, the ratios of intermittent renewables in the energy systems increased. As energy systems became more increasingly integrated nationally and internationally, energy flexibility and energy sector coupling processes became the new order of the day. The Danish district heating sector now faced a new set of challenges and potentials. A key challenge for the sector was increasing biomass import dependency.

DH suppliers throughout Denmark had successfully integrated large ratios of renewable energy resources, most notably biomass, into the district heating systems over a relatively short time [6,39,62] (see Figure 9 and Figure 10). This transitional process emphasized the technical diversity, flexibility, and adaptability of the Danish district heating sector. However, the growing biomass demands also led to increasing volumes of biomass imports from various European countries, as well as from the USA, Russia, North America, and South America [81]. Various stakeholders increasingly (and rightly so) questioned just how sustainable these large-scale biomass imports were [62,82]. Ironically, then, in the face of the global climate crisis, and just decades after the collective experiences of oil-import dependency during the global energy crisis of the 1970s, the rapid transitional process of the Danish district heating sector had resulted in fuel import dependency yet again.

Novel potentials of the Danish underground heat supply infrastructures were also revealed, however. The district heating infrastructures facilitated energy flexibility, and thereby also energy sector coupling [7,8,11,12]. Notably, research suggests that, internationally, district heating technologies may provide heating and cooling solutions in future ‘smart’ energy systems at markedly lower costs than alternative solutions [83,84].

The Energy Roadmap 2050, a report from the European Commission, proposes six strategies for reaching the EU annual greenhouse gas reduction target of 80% in 2050 compared to the year 1990 [85]. Interestingly, these scenarios do not involve large-scale district heating, but instead focus on electrification of the heat sector (e.g., via heat pumps) and electricity savings.

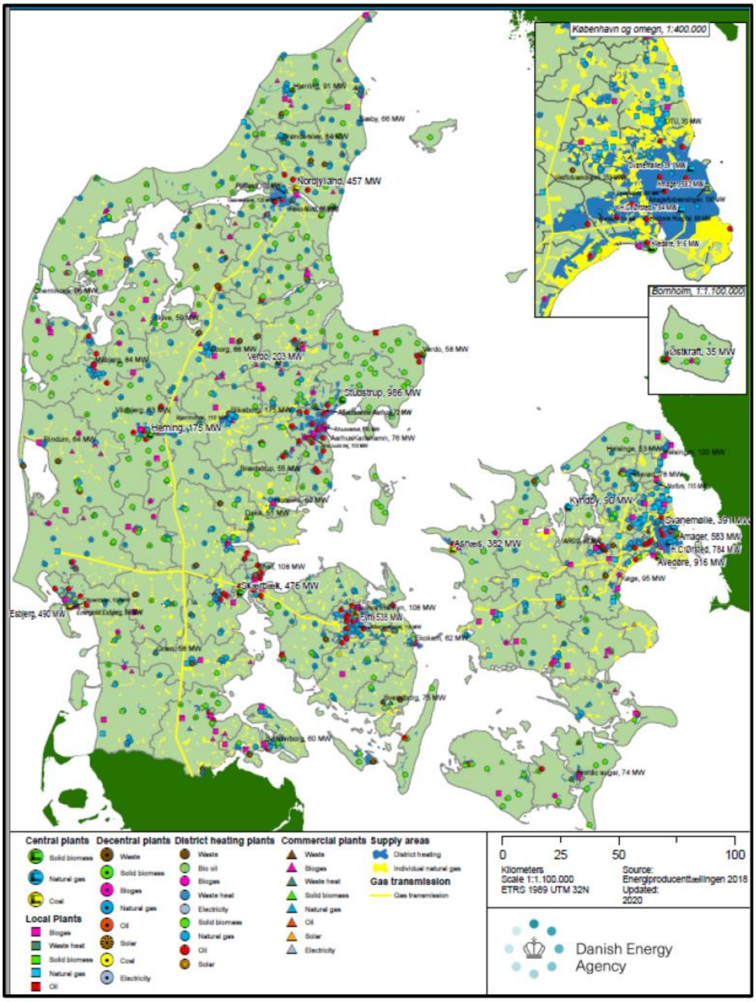

Figure 10: Danish heat supply infrastructures in 2020. Source: [86].

Discussion

This section discusses insights and lessons that may be drawn from this brief socio-technical account. It also highlights paradoxes and questions raised by way of this socio-technical journey. It discusses: (1) the role and importance of collective societal memories and time, (2) the possible sustainability flipsides of current norms and standards for heat supply service provision, and (3) raises key methodological questions via-a-vis the translation of contextual lessons across time(s) culture(s), and place(s). Finally, (4) the noted and striking similarities between the global energy crisis of the 1970s and the 2020s raise (perhaps slightly uncomfortable) sociopsychological questions.

The discussion is not to provide answers, but rather zooms in on tacit, and perhaps overlooked, frictions, dilemmas, and their consequent policy challenges. Hopefully, this will inspire enriching debate and future research enquiry.

Reliable and Affordable Heat Supply Provision as Policy Priorities

Global historical events, and their national repercussions, informed the Danish history of district heating and CHPs. This section considers the role and importance of national scale collective memories and temporal distance (i.e., distance in time) for this historical journey.

Collective memories of energy resource scarcity during the World Wars and the global energy crisis in the 1970s motivated support for CHPS and DH among the Danish public and among the political leadership. Throughout later decades, the lingering Cold War tensions provided a constant reminder of this national history of *energy import dependency*. In this light, the *energy independence potential* of the Danish North Sea oil and gas, and the strategic integration of this natural gas into the Danish energy system, was highly attractive. Ownership issues and the economy were the topics of public protests and contestation at the time (see Section 4.4).

Interestingly, popular historical accounts of the Danish energy system often downplay (if not downright ignore) the economic role and importance of the Danish North Sea oil and gas for not only the Danish energy system, but also for the Danish welfare state. Questions of why linger.

As collective memories of the global energy crisis faded through time, and as the Danish energy system evolved and improved, energy supply questions were no longer topics of public debate. According to sector professionals, local engagement and interest in energy supply questions dwindled. Consumers, or end-users, had increasingly come to expect the reliable and affordable heat service provision that had now become the norm. Meanwhile, the norms for what constituted ‘normal’ inside temperatures gradually crawled up the scale on the thermometer [23,46]. So, as the collective memories of energy resource scarcity faded, environmental awareness and concern grew among the Danish public. Meanwhile, the norms for minimum or ‘normal’ inside temperatures called for warmer and warmer temperatures inside. This paradox, too, remains strangely overlooked in public and political debates.

Reliable, Affordable, and Invisible Heat Supply Provision: The Flipsides?

The DH sector norms of affordable, reliable, and invisible heat supply service provision may not be conducive of more sustainable end-user/costumer heat consumption behavior. Indeed, perhaps quite to the contrary. This reasoning is underpinned by various observations. The underground nation-wide network of heat supply infrastructures throughout the rural and urban Danish landscapes have lived rather quiet lives. In part, this may be because these underground energy infrastructures are less visible in the landscape than, for example, the aboveground wind farms are. Additionally, the district heating community norms for good heat service provision are reliable, stable, affordable, and invisible heat service provision that ‘just works’ [87]. As a result, the heat (and energy) consumed for maintaining certain inside temperatures is easily accessible and intangible for the ordinary end-user/consumer.

However, the intangible nature of heat for heating combined with the easy use of this energy resource for end-users may lead to less conscious energy usage among the end-users, perhaps ultimately leading to excessive energy usage. Within related research domains, variants of this phenomenon are known as the “rebound effect”, see [88,89]. So, judging by research on the ‘rebound effect, a flipside of the DH sector norms and standards for good heat supply service provision may be increasing or growing heat demands among the end-users.

As we discuss below, the energy crisis of the 2020s may have changed this, however.

The Importance of Context: What Can We Learn from History?

This brief historical account raises the key methodological question: To what degree—and how—may contextual lessons learnt be translated across time(s) culture(s), and place(s), if at all?

Certain contextual factors and phenomena were fundamental for, and underpinned, the historical sociotechnical trajectories of DH and CHPs in Denmark. For example, (I) the collective societal memories of energy resource scarcity, and (II) the bottom-up tinkering, pragmatic problem solving, and innovative drive from the early days of Danish district heating gradually translated into almost a *culture* of re-use, recycling, and energy efficiency. This culture underpins the Danish district heating communities today [87]. (III) From the top down, a political culture of broad political coalition agreements allowed for the long-term strategic energy planning that spanned decades. Finally, (IV) high levels of general societal trust and low levels of corruption facilitated the broad public support for these large-scale energy planning initiatives [90,91].

Interestingly, district heating and collective heat infrastructure planning are most common in the former USSR, in China, and in Scandinavia [20]. In comparing these political systems or regimes, the Scandinavian social democracies stand out with mixed economies, high levels of general social trust, and very little corruption [90,91]. Much has changed in the Denmark since the 1980s and the 1990s, when the national-scale heat infrastructure planning initiatives were first carried out. Experts involved in the energy planning initiatives at the time held that similar initiatives would *not* be publicly supported, or even possible, today. These expert interviews were carried out immediately before the global energy crisis of the 2020s, however. No-one could have predicted these future global events, nor the scale of their global impact, at the time. In view of these global and national sociotechnical dynamics and change-processes, perhaps the experts would have answered differently now.

So, can contextually bound historical insights and lessons learnt be translated across contexts? And if so, to what degree? The answer to this highly relevant question could be some variant of: “it depends!” Perhaps followed by: “what is the alternative?” After all, while we cannot learn from the future, we can do our very best to learn from the past. In seeking to learn from these invaluable lessons of history, we should account for the role and importance of *context*, at various levels, and at various domains. This implies considering the interchanging sociotechnical dynamics associated with, for example, historical time(s), specific national, local, or organizational culture(s), and relevant geographical sites or place(s). In this way, via careful cross-cultural analysis, the insights and lessons that can be drawn from historical successes and failures may inform similar socio-technical journeys elsewhere.

Back to Square One? Energy Security Versus the Climate Change Challenge

There are striking similarities in public and political reactions towards the global energy crisis of the 1970s and the 2020s.

For example, (i) it seems that the energy crisis of the 2020s has resurrected the rhetoric of energy independence, energy security and energy affordability (see Section 4) from the embers of the Cold War. Climate change, and climate change-related issues, now seem of secondary concern in public debates. (ii) What were previously referred to as almost sacrosanct norms for comfort (i.e., the norms for ’appropriate’ inside temperatures) are once again debated, and the Danish public has miraculously found ways to save energy (see reports on this at ens.dk.). From the top down, (iii) the Danish Government has initiated remedial energy sufficiency measures, for example, the relaxation of sustainability criteria for certain fuels.

So, what do these reactions/responses to the 2020 energy crisis imply for low-carbon energy transition processes?

Positively, and in terms of change readiness among the public, this global energy crisis has showed that we can change our energy-related behaviors quickly. Less positively, however, these reactions also emphasize that we prioritize the comfort and the challenges of the here and now. After all, the *short-term* societal challenges of energy insecurity and growing energy costs are now the key foci of public debates, with sustainability-related issues and environmental concerns all but removed from the agenda. Thus, the *longer-term,* more abstract, and more psychologically distanced [92,93] public and political concerns (e.g., climate change and climate change-related challenges) are overshadowed by the more psychologically proximate energy crisis that is a crisis of here and now.

Indeed, judging by popular and political debates, the more psychologically distanced climate change challenges have aptly faded into the corners of our individual and collective attentive spheres, superseded by the day-to-day challenges afforded by the current energy crisis. These observations call for systematic mapping of - and research enquiry into—our associated fundamental social psychological consumption-related rationalization processes.

Positively, recent years have also seen rapidly growing climate consciousness and proactive engagement among particularly the younger generations. This suggests that they perceive climate change-related issues as pressing and as more psychologically proximate.

Conclusions

The WEC has ranked the Danish energy system among the top countries in the world according to the energy trilemma criteria: energy security, energy equity, and sustainability. Although DH, CHPs and their associated technologies are pivotal for this top WEC ranking of the Danish energy system, their importance is largely overlooked internationally. Energy planners and district heating professionals have long called for more international focus on the unique history of DH, CHPs, and large-scale energy planning in the Danish energy system. Setting out to fill this gap in the literature, this brief history of DH and combined heat and power in Denmark explored how historical events, societal dynamics, and changing political and social rationales have all informed the emergence and the evolution of the underground heat supply infrastructures throughout rural and urban Danish landscapes.

After the global energy crisis in the 1970s, the public and political sentiment called for energy independence, alternatives to imported fuels, and for alternatives to nuclear power. The overarching energy policy priorities: energy independence, fuel diversification, energy efficiency, and later sustainability, were operationalized in the Heat Supply Act, which provided the legal framework for the national-scale collective heat infrastructure planning initiatives ahead. Broad political coalition agreements allowed for the necessary long-term strategic heat supply infrastructure planning initiatives. The Heat Supply Act granted wiggle room for bottom-up initiatives and experimentation. High levels of general societal trust, low levels of corruption, and collective memories of the energy crisis, may all have contributed to the broad societal support for these large-scale collective energy infrastructures. In the following decades, growing environmental awareness and concern called for renewable energy resources as alternatives to fossil fuels.

The paper suggested that a mindset (or even culture) of innovative thinking, heat re-use/re-cycling, and energy efficiency focus still characterizes the Danish district heating communities today. It noted the DH sector norms for good heat supply service provision as being affordable, reliable, and rather quiet heat supplies, and discussed how consumption of such highly intangible energy (here energy in the form of heat) may lead to less conscious energy usage, and ultimately perhaps to excessive energy usage, among the end-users.

Interestingly, the energy crisis of the 2020s demonstrated how quickly end-users could, once again, refocus on - and reduce - their use of energy, including heat. In facing these contemporary energy security-related grievances, the public and political debates have aptly swept climate change issues and sustainability concerns aside. Echoing public and political rationales from the global energy crisis almost half a century ago, energy security and energy price-related issues have, once again, taken center stage.

Perhaps history, and historical sociotechnical trajectories, did grant the Danish energy system a head start in the global race towards low-carbon energy transitions. Yet, as this paper revealed, that route may not have been quite as direct as popularly portrayed. The Danish district heating sector currently faces the challenges of growing biomass import dependency, but also the potentials of sector coupling and energy flexibility. Research suggests that energy efficiency and energy flexibility potential may be harvested via district heating and district cooling solutions in future 'smart' energy systems all over the world. To this end, and for other countries embarking upon the low-carbon energy transitions journey, hopefully the insights and lessons drawn from this condensed account of district heating history in Denmark may prove both valuable and inspirational.

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