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A comparative analysis of policies and strategies supporting district heating expansion and decarbonisation in Denmark, Sweden, the Netherlands and the United Kingdom – Lessons for slow adopters of district heating

Daniela Salite[a,*,1], Ying Miao[b,*,2], Ed Turner[b]

[a] Department of Physical and Environmental Sciences, University of Toronto Scarborough, ON M1C 1A4, Canada
[b] Department of Politics and International Relations, Aston University, Birmingham B4 7ET, United Kingdom

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ABSTRACT

This paper undertakes a comprehensive comparative analysis of policy challenges and opportunities for the deployment of low-carbon DH. Through literature review and complementary qualitative analysis of interviews with key institutional stakeholders in the heating sector (n= 20) of Denmark, Sweden, the Netherlands, and the UK, the paper draws some important lessons on preconditions for successful roll-out of DH. We find that more governments must create appropriate conditions, provide more support, and speed up actions to enhance the role of DH in heat decarbonisation, to educate, encourage the adoption, and involve citizens, politicians, and other key stakeholders in the heat transition to DH. Amid the current energy price crisis, slow adopters must act fast to develop low-carbon DH networks to ensure the supply of secure, sustainable, and affordable heating sources. They would have to create appropriate conditions to reduce fossil-fuel path dependence, lock-out fossil fuel-based infrastructure and lock-in the diffusion and adoption of low-carbon DH.

1. Introduction

Heating is an important aspect of energy use in Europe, accounting for approximately 50 % of their final energy demand (Mathiesen et al., 2019). European heating systems are mainly reliant on fossil fuels, particularly gas which supplies 42 % of heat demand (Kerr and Winskel, 2021). The UK, the Netherlands, and Germany are among the most gas-reliant countries – a reflection of the national resource endowments, technical infrastructure, governance approaches, and past and present regulations and policy choices (Kerr and Winskel, 2021; Magnusson, 2016). Fossil fuel-based heating have historically led to increasing returns (path dependence), making other heating technologies uncompetitive in price and performance (Gross and Hanna, 2019). However, as concerns over environmental sustainability and the need to reduce greenhouse gas (GHG) emissions and reliance on Russian gas supply increase in Europe and globally, there is a need to transition to low-carbon heating sources.

Achieving Net Zero by 2050 is a key energy and climate policy priority, but meeting such an ambitious goal is challenging and requires a complete energy system transformation (Mathiesen et al., 2019), including significant additional investment in new low-carbon heating technologies (e.g., heat pumps - HP, biomass boilers, district heating - DH) and infrastructure (e.g., pipes and substations) (IRENA, 2017; Sahni et al., 2017). DH has been widely acknowledged as one of the most sustainable, economically viable, faster, and efficient solutions for heat decarbonisation in buildings and most industrial processes (Li et al., 2015; Millar et al., 2019). DH is a centralised system that uses heat and fuel sources that would otherwise be wasted to supply space heating and hot water to end-users through a pipe network (Li et al., 2015; Martinopoulos et al., 2018). DH allows for the integration of flexible and clean energy sources (including waste heat and renewables) into the energy mix, which could be challenging at individual buildings in dense urban areas (IEA, 2023). As such, DH has attracted a growing interest from European countries, including from the Netherlands and the UK where it remains underdeveloped with less than a 5 % of shares (BEIS, 2018; Li et al., 2015).

DH currently covers 12 % of heat demand in Europe, and is well-established in Denmark, Estonia, Lithuania, Slovakia, and Sweden,

* Corresponding authors.
E-mail addresses: daniela.salite@utoronto.ca (D. Salite), y.miao2@aston.ac.uk (Y. Miao).
[1] ORCID: 0000-0001-8204-408X
[2] ORCID: 0000-0001-9405-6387

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providing more than half of the domestic heating (Kerr and Winskel, 2021; Martinopoulos et al., 2018). However, in many countries in Europe and globally, DH mostly relies on fossil fuels (e.g., coal and gas) for heat production (IEA, 2023). Yet, there is significant potential to upgrade existing fossil-fuel-based DH systems and to expand and create new networks using low-carbon energy sources such as solid biofuels, solar and geothermal (IRENA, 2017). Thus, European countries are taking diverse approaches to scale-up the decarbonisation and expansion of low-carbon DH in line with their climate change mitigation goals and to increase energy security and efficiency (Gorroño-Albizu and de Godoy, 2021). This study analysis some of these approaches by taking Denmark, Sweden, the Netherlands, and the UK as examples.

Many studies have looked at heat decarbonisation through diverse technologies and at different geographic scales (e.g., Kerr and Winskel, 2021; Mathiesen et al., 2019; Sovacool and Martiskainen, 2020), but fewer covered the decarbonisation of DH (e.g., Gonzalez-Salazar et al., 2020; Reda et al., 2021). Moreover, studies have enhanced the success of Scandinavian countries (e.g., Johansen and Werner, 2022; Magnusson, 2016), but very few critically looked at the relative effectiveness of their policies to develop DH systems (e.g., Donnellan et al., 2018; Egüez, 2021). Sahni et al. (2017) state that lessons can be learned from available evidence of best practice and policies around the globe. However, we argue that better lessons can be learned from both positive and negative practices and policies – therefore a symbiosis of "most similar" and "most different" case selection. The latter can stimulate the understanding of barriers to adoption, creating opportunities to improve the current practices and policies and bring better outcomes. Thus, within this context, we undertake a comprehensive comparative analysis of both policy challenges and opportunities for the deployment and uptake of low-carbon DH, taking Denmark and Sweden as the examples of successful countries in DH development. This aims to draw some lessons on what factors promote and hinder the uptake of low-carbon DH for laggard cases such as the Netherlands and the UK that are embarking on the expansion of low-carbon DH and reduction of heat demand.

We draw on the political-economy perspective of energy transitions to explore and disentangle governance structures, actors, and politics that underpin the development and uptake of DH. We analyse the role of municipalities' heating planning and implementation capabilities in the deployment of DH. We examine the range of measures implemented to de-risk investment in DH, aid the development, management, and uptake of DH, improve energy efficiency, and reduce energy demand of the built environment. We then turn to an analysis of why these successful countries have followed different pathways, and the opportunities and challenges of the policies and strategies implemented to aid the planning and development of DH. This is followed by a reflection of the useful lessons learned for countries such as the Netherlands and the UK.

2. Historical DH development and decarbonization in Europe

The study of the political economy of energy transition is important to better understand the politics and power relations that drive the transition, particularly the understanding of who determines the terms of the transition and how, the different actors, and their forms, roles, and relations of power, the nature of the interests or resistance (Baker et al., 2014; Power et al., 2016). This understanding provides a useful starting point for this study to explore the agendas, activities, and sociotechnical dynamics of the transition, including path dependences, lock-ins and the differential key policies, initiatives and abilities to enable the transition.

The transition away from fossil fuel-based heating to DH in Denmark and Sweden occurred during the second half of the 20th century as a result of energy security concerns and price increase due to the oil crisis in the 1970s (Sahni et al., 2017). The crisis created the urgency to reduce dependency on energy import and to pursue diversified, available, stable, and affordable energy sources, resulting in policymakers aggressively encouraging the expansion and use of DH (Johansen and Werner, 2022; Sovacool and Martiskainen, 2020). The gradual increase in environmental awareness due to acid rain in the 70 s[3] and the amplification of the international debate on climate change mitigation amplified between 1980s and 1990s also contributed to intensifying the urgency for the expansion and use of DH (Johansen and Werner, 2022; Werner, 2017a).

To aid the transition to DH, Denmark and Sweden developed and implemented a combination of legislations, regulations, heat infrastructure planning, energy efficiency measures, and recommendations (Martinopoulos et al., 2018; Mathiesen et al., 2019). These measures also intended to ensure energy security, enable the reduction of energy consumption) (Mathiesen et al., 2019), while also addressing fuel poverty, which remains an issue in Europe with more than 35 million people still unable to afford adequate heating services to fulfil their basic needs such as lighting, cooking, charging appliances and heating (Lloyd, 2022). This shows that heating services not only require decarbonisation but also a significant expansion to address fuel poverty (Sovacool et al., 2021b).

To continuously address climate change concerns, currently these countries have focused more on the decarbonisation of existing DH and the expansion of low-carbon DH by taking advantage of their renewable resource potential or creating policies to promote further uptake (Hast et al., 2018; IRENA, 2017). Sweden powers its DHs with waste from its extensive forestry industry (around 74 %), waste energy from industries (8 %), large HP (7 %), fossil fuels (7 %), recovered gases (2 %), and peat (2 %) (Kerr and Winskel, 2021).

Denmark uses biofuel to power around 60 % of its DH but is currently facing some challenges to decarbonising the remaining DH powered by coal (20 %) and gas (20 %) (Kerr and Winskel, 2021), including increasing biomass import dependency and the integration of non-combustion heat generation methods into DH systems (Reda et al., 2021). Ćosić et al. (2012) argue that additional efficiency measures may be needed to reduce biomass demand or to increase investment in other renewables (e.g., solar and wind), but high investments in energy storage systems will be required to use them effectively due to intermittencies. Lund et al. (2014) suggest that efficiency of renewables in DH can be achieved with the integration of HP, combined heat and power (CHP) and heat storage. An analysis conducted by Lygnerud et al. (2021) on the widespread integration of HPs in DHs as a business model in Sweden shows that the model can be profitable and sustainable, with maximum cost savings of 33 % and CO_2 emissions savings of 75 %.

Johansen and Werner (2022) foresee an increased role of non-combustion heat generation through HP, solar thermal collectors, and waste heat from industries. Nonetheless, this increased focus on energy efficiency, business models and decarbonisation has contributed to the DH technology development, leading to its fourth (4GDH) and fifth generation (5GDH). These latest generations have lower supply temperature, which ensures less heat loss within the DH network. The 4GDH has supply temperature level at a maximum of 60–70 °C and aims to reach a renewable energy-based heat supply (Lund et al., 2021). While the 5GDH, which is combined with a cooling system, has ultra-low temperature that requires boosting with HP to reach the required temperature level at the end-user (Lund et al., 2021). This heat and cooling combination can be ideal under the current scenario of weather extremes. However, the existing complexities related to the design and operation of this new generation because of the lack of technical standards and guidelines constitute a challenge for its development or integration into existing systems (Dang et al., 2024). Moreover, the deployment of 5GDH is costlier due to more expensive substations, large pipe diameters and storage capacity, the installation of an individual domestic hot water tank, higher pumping cost per unit of energy and high electricity costs for HPs (Buffa et al., 2019; Dang et al., 2024).

The third-generation DH, remain the most common type of the technology in Sweden, the UK, and the Netherlands (Lund et al., 2021;

[3] Interview Swedish Energy Agency, April 2022

Millar et al., 2019; Lavrijssen and Vitéz, 2021). It has heat supply temperature below 100 °C, which is an improvement in the distribution efficiency from the superheated water and steam carrier used in the second and first generations, respectively. However, gas-based heating remains dominant in the Netherlands (85 %) and UK (94 %). Gas also powers most UK DH systems through CHP systems and small co-generation plants, with some of the small plants recently starting to deploy biomass (Collier, 2018).

In most countries, heat remains prone to strong path dependence and lock-in that resist change (Gross and Hanna, 2019; Sovacool et al., 2021a). Thus, policymakers seeking to achieve low-carbon emission targets have the challenge of creating conditions to encourage the adoption of low-carbon heating solutions, including addressing the socioeconomic drivers such as income and poverty (Sovacool et al., 2021a), which are crucial to address fuel poverty. Policymakers also have the challenges of dealing with the whole web of infrastructure and building stock required for the transition, patterns of incumbency and path-dependence (Sovacool et al., 2021a). With this in mind, we aim to understand from Denmark and Sweden, what conditions are necessary to support the development and uptake of low-carbon DH in countries like the Netherlands and the UK where it is relatively underdeveloped.

3. Methodology

This cross-countries analysis is centred on Denmark, Sweden, the Netherlands, and the UK. We balanced the selection of countries based on the geographic location, climate-related heat demand, energy resources, shares of DH in the heating systems, and plans and commitment to decarbonise and expand DH by 2050 (see Table 1). The selected countries have moderate to cold climates, with winters lasting between 4 and 5 months. Denmark and Sweden have successfully secured high shares of DH and extensive DH networks, making the former a leader of all European countries in terms of trench length and per capita use of DH network (Johansen and Werner, 2022; Sovacool and Martiskainen, 2020). The Netherlands and the UK aim to achieve a tenfold increase in DH shares to 50 % and 20 % by 2050, respectively (Beckman and van den Beukel, 2019; BEIS, 2021c).

This qualitative and comparative case study was mainly built upon desk research and twenty semi-structured online interviews with key institutional stakeholders in the DH area (see Table 2). The desk research comprised peer-reviewed literature, and institutional documents, reports, and briefings on topics related to DH, heating sector, sustainable energy transition, governance, and political-economy. It sought to collect information on the set of policies, regulations, socio-technical conditions, institutions, and actors' configurations that shapes the transition to sustainable heat technologies.

The interviews intended to collect stakeholders' viewpoints on the main policy and regulatory challenges and opportunities to advance the develop DH and expand low-carbon DH, reasons behind the success (or slow progress) of DH in their countries. This aimed to increase the understanding of how governments can scale-up the deployment of DH. Thus, interviewees were purposively selected based on their expertise after an online search of main institutions working in the DH area in each study country. In cases where the selected interviewees were unavailable, we reverted to snowball sampling with the interviewees kindly suggesting an expert to replace them. The interviews were transcribed and coded in NVIVO using thematic analysis to better capture, interpret and analyse stakeholders' viewpoints.

4. Policies and initiatives for DH development

Achieving the full DH potential in heat decarbonisation requires effective policies and measures to address financial, regulatory, and social barriers to the deployment of renewables in existing and new networks (IRENA et al., 2020). European countries have increasingly used a mix of policies to prohibit the use of fossil fuel-based heating sources, and to drive the transition to DH (Kerr and Winskel, 2021), as described below.

4.1. Heating planning and implementation

In all study countries, municipalities were crucial in the development of heat planning and implementation, and they have implemented some diverse and similar strategies to accelerate the transition to DH and de-risk investment. The Danish municipalities were responsible for carrying out heating planning, assessing the socio-economic and environmental impacts of heat infrastructure projects, approving, or dismissing new projects, and ensuring that the extension of and changes in DH systems are in line with the heating supply law (Johansen and Werner, 2022). The existence of technical standards and guidelines for DH development was critical for the creation of a safe investment environment, dissemination of information and knowledge within the sector, and for shaping the market for suppliers of technical equipment, and thus, improve the availability of and compatibility between different components in the DH systems and reduce their prices (Danish Board of District Heating – DBDH, 2022; Ericsson, 2009). It has also been important to create a good environment for co-operation between DH companies, suppliers of equipment and consultants (Ericsson, 2009).

The Danish municipalities were also responsible for the enforcement of a mandatory connection policy to DH[4] (dismissed in 2019) and the payment of a fixed subscription fee (even without using DH) to ensure a minimum of customers and sales, and thus reduced investment risks in DH (Danish Energy Agency, 2017; Sovacool and Martiskainen, 2020; Johansen and Werner, 2022). One expert from DDHA (April 2022) explained that "*if you want to develop DH in an area, you need a critical mass of connections to de-risk investment, to make the investment financially viable or feasible*". The advanced DH development led the country to become the base of many companies involved in diverse areas of the DH sector, including the design, engineering, construction, and manufacturing of different DH components (Danish Energy Agency, 2017). Many of these companies such as Danfoss and Logstor, have also expanded their activities internationally, including in the Netherlands, Sweden, and the UK (Danish Energy Agency, 2017). After the successful DH deployment, currently DH has shifted its focus to research and innovation as explained by a DTU expert (June 2022):

> *"Scandinavian countries are so mature that DH now is not much about expansion but more like going towards the modernizations of the existing assets, the development of new technologies, and the digitalization to secure low temperatures operations. This is great because it could be easily replicated in less mature markets."*

Dutch municipalities are also responsible for developing heat plans for up to 10 years (BEIS, 2020), after considering and discussing all options with the citizens, political parties, and representatives.[5] They also emulates the Danish mandatory connection to DH in new buildings but allows disconnection if the supply agreement was made after the introduction of the new heating Act (into effect since July 2019), and if disconnection is technically possible or not detrimental to other users (ACM, 2019). Consumers who are allowed to disconnect are legally required to find heating alternatives that are as sustainable as DH.[6] However, the revised act does not prevent heat suppliers from applying maximum disconnection rates as stipulated in the heat supply agreement (ACM, 2019). Collectively, we find that while the act intends to encourage consumers to connect and stay connected to DH, it raises significant equity and justice concerns between the different categories of dwellers, according to their property types and the issuance of their DH supply contracts. Despite allowing disconnection, the act makes

[4] Interview DDHA, April 2022
[5] Interview PBL, April 2022
[6] Interview ACM, May 2022

Table 1
Description of the study sites (Source: adapted from Beckman and van den Beukel, 2019; BEIS, 2021c; Danish Energy Agency, 2017; Donnellan et al., 2018; Kerr and Winskel, 2021; Sovacool et al., 2021a; Thornton et al., 2017; Werner, 2017a).

Country	Geographic location	Climate	Winter Period	Number of DH systems	Length of the network (kms)	Number of DH companies	Supply Share of DH (%)	Planned share of DH by 2050 (%)
Denmark	Northern Europe	Moderate	October - April	460	60,000	Over 400	64	-
Netherlands	North-western Europe	Moderate	November – March	6913 (13 large-scale)	4000	Around 20	5	50
Sweden	Northern Europe	Cold	October - April	500	23,400	Over 200	50	-
UK	North-western Europe	Moderate	November – March	5500	1800	-	2	20

Table 2
List of interviews conducted by country.

Country	Institution interviewed	Number of interviews
Denmark	Danish District Heating Association (DDHA)	1
	Danish Utility Regulator (DUR)	1
	Danmarks Tekniske Universitet (DTU)	1
	Municipality of Aalborg	1
Sweden	e.on Ectogrid	1
	Halmstad University	1
	Lund University	1
	Swedish Council for DH	1
	Swedenergy	1
	Swedish Energy Agency	1
	Vattenfall	1
Netherlands	Cooperatie Energie Samen	1
	Eneco	1
	Energie-Nederland	1
	PBL Netherlands Environmental Assessment Agency (PBL)	1
	The Netherlands Authority for Consumers and Markets (ACM)	1
United Kingdom	Heat Network Associates (HNA)	1
	The Association for Decentralised Energy (ADE)	1
	Building Low Carbon Solutions	1
	University of Sussex Business School	1
Others	Euroheat and Power	1
Total		**20**

disconnection of consumers from apartment buildings much harder than from individual or terrace properties.[7] Moreover, the penalties and technicalities of disconnections make disconnection mostly possible for those dwellers in better socio-economic and financial conditions. These concerns highlight the need to have strict DH regulations to ensure quality services, fair and affordable supply prices. Thus, the country is preparing its Heat Act 2.0 (to be implemented in 2025), which will set sustainability standards and safeguard the quality, reliability, and affordability of the heat supply (Herreras Martinez et al., 2023).

In contrast, Sweden has no mandatory connection, and allows customers to disconnect within 3-months of notice.[8] Although Swedish municipalities are responsible for developing energy plans and have a monopoly planning of DH development, building owners to decide on their sustainable heating source as long as they follow environmental standards.[9] However, to deploy DH, Sweden built DH in major towns in the 1950s and 60 s and connected to DH a million new homes built between 1965 and 1974 to address a severe house shortage (Di Lucia and Ericsson, 2014; Werner, 2017a). After covering much of the primary market, during the 1990s Sweden built small-scale DH systems and expanded it to low heating density areas through investment grants available for both municipalities and households (Werner, 2017a). Despite a strong resistance from incumbent actors such as heating oil vendors (Dzebo and Nykvist, 2017), the country's great focus on quality of service and on wider considerations (e.g., environmental impacts) (Donnellan et al., 2018), rather than on penalties and technicalities of disconnections, seems to have been sufficient to drive consumer's demand for DH connections and to avoid disconnections. As explained by one expert from Swedish Council for DH (May 2022), "*now DH is a natural part of urban infrastructure in Sweden and most people do not even know that they have heating from DH; it's just something similar to water and electricity, you just have it, and nobody really bothers*".

While this non-mandatory connection strategy worked well in the past, nowadays, it can be too risky for businesses if people decide not to connect to DH, and to overcome that risk it would require to somehow force buildings to connect.[10] This would be very challenging with the current regulation in Sweden favouring more HPs,[11] which led the country to have the second highest global penetration of HPs, with 1.9 million installed HP (43 % of households) (Calcea, 2022). Around 2 % of these households (in multi-family residential properties) are still connected to DH and using it when the HP capacity is insufficient to meet the building heat demand (Lygnerud et al., 2021). There is a general assumption in Sweden that HPs is overtaking market share from DH because of the growing consumers' awareness of the financial, energy savings and environmental benefits of the technology and desire to have more autonomy (Lygnerud et al., 2021; Swedish Cooling and Heat Pump Association, 2023). In fact, HP are gaining more attention globally compared to DH, including in the UK and the Netherlands where the uptake in 2023 increased by 4 % (around 60,000 units) and 53 % (153, 980 units), respectively (European Heat Pump Association – EHPA, 2024). Some HP experts describe it as a preferable technology to replace gas-based heating. This shows how policy development and support for new technologies as well as public awareness can change the direction and speed of their implementation and make them more competitive.

In the UK, local authorities, connecting council, and community buildings have also historically driven the installation of DH systems serving domestic consumers (Thornton et al., 2017). Local authorities issue planning permission and coordinate with customers to foresee the initial heat demand baseload required for DH network development (Ofgem, 2016). There is also no obligation to install renewable heat options yet (Collier, 2018). Thus, this together with the growing attention to HP in the UK, led companies (e.g., EQUANS, EnviroEnergy) to de-risking their investment in DH by making customers along the DH network connect or remain connected to the network. Nonetheless, as part of its 'Heat and Buildings Strategy' to support the scale-up and uptake of low-carbon DH, the UK proposes the introduction of heat network zoning in England by 2025, with local authorities responsible for identifying and appointing areas best suited for the development of low-carbon DH (BEIS, 2021a). This measure adopted from Denmark requires the connection of certain buildings (to be defined) in the zoning within a set timeframe and to use the heat provided, unless exempted (BEIS, 2021a). It also intends to give project sponsors and investors greater assurance of DH business case (BEIS, 2021a). The UK is also

[7] ibid
[8] Interview Halmstad University, April 2022
[9] Interview Swedish Energy Agency, April 2022
[10] Interview e.on Ectogrid, May 2022
[11] Interview Vattenfall, April 2022

finalizing the development of its Heat Networks Technical Assurance Scheme (HNTAS) to provide the necessary governance, structures, procedures, and standards required to assess and certify DH to ensure high performance, and reliability, and good consumer outcomes (Jones et al., 2024).

While customer base is important to de-risk the business, we see the provision of policy and regulatory measures and incentive to develop DH and to avoid mass disconnection as equally important, considering the amount of investment required for DH networks and the time required for investment return. Such legal measures must be in place now to avoid further delays in the implementation of DH projects as has already happened with the implementation of some policies (e.g., Clean Growth and NetZero strategies) as a result of the long process of Britain's exit (Brexit) from the European Union (EU) since the government dedicated its capacity to 'getting Brexit done (Blondeel et al., 2022). Therefore, the UK government must stay focused on its commitment and deliver sustained actions to overcome the current lack of urgency and uncertainty in the implementation of the strategies to reach the country's net zero targets (CCC, 2023). However, the government plan to annually issue hundreds of new oil and gas licenses in the North Sea to strength the nation's energy security and give an assurance to investors, instead of investing in more renewables, shows the persistent challenges that the country faces to reduce its fossil fuel dependence and to commit to its net zero targets.

Meanwhile, in 2018, the Dutch government made a more sustainable decision to halt the extraction of gas in Groningen to reduce seismic risks and the use of fossil fuels. Additionally, Denmark also made more ambitious decarbonisation plans in 2022 to connect around 50 % of the 400,000 households that are currently using gas-based heating to DH by 2028, and the remaining 50 % to switch to HP or biogas by 2030 (Ritzau et al., 2022).

4.2. Financial and fiscal measures

Denmark and Sweden have introduced several financial and fiscal measures (e.g., credits, tax reduction, subsidies, grants, and loans) to offset the high capital costs and financial risks associated with DH development and uptake, and to encourage the integration of renewables into DH systems (IRENA et al., 2020; Kerr and Winskel, 2021). The Danish historical massive public commitment and investment in the DH sector has allowed the development of large-scale DH projects with competitive prices and the creation of a market for private investments in the sector (Danish Board of District Heating – DBDH, 2022). Municipalities sometimes developed cross-municipal partnerships to fund projects (Danish Board of District Heating – DBDH, 2022) and they also implemented a loan scheme, offered via Municipal credit Bank (KommuneKredit) with an extremely long-term payback period of between 20 and 50 years and low-interest rates (Johansen and Werner, 2022; Ramboll, 2022). Central authorities offered strong investment subsidies to utilities that rehabilitated and completed DH networks and consumers who installed central heating and connected to DH (Danish Board of District Heating – DBDH, 2022). There was also a joint investment from local initiative groups for the development of DH owners by cooperatives (DBDH, 2022). While international credits at the lowest market-based interest rate were available to fund most companies' investments in DH, and banks competed to offer the best conditions where the security was high (Danish Board of District Heating – DBDH, 2022).

In Sweden, there have also been a number of investment subsidies and favourable loans available for DH utilities (Ericsson, 2009). For example, the government subsidies provided through the Local Investment Programmes (LIP) and the Climate Investment Programmes (Klimp), introduced in 1998 and 2002, respectively, to strengthen environmental initiatives to reduce GHG emissions and encourage cooperation between stakeholders (e.g., municipalities, industries, and organization) at the local level, including for the development of DH projects (Ericsson, 2009). Also, the government subsidies provided to households between 2006 and 2010 to switch from oil and direct electric heating to DH (Donnellan et al., 2018; Ericsson, 2009). Bank loans such as from the European Investment Bank (EIB) and Nordic Investment Bank have also been essential for DH development, expansion, and upgrade, particularly for the private sector (European Investment Bank – EIB, 2014). Moreover, the cooperative investment from and collaboration between DH companies have allowed the further expansion and interconnection of existing DH networks between cities and towns (Donnellan et al., 2018).

The Dutch government does not offer the same level of financial support to companies for the development of DH project seen in Denmark and Sweden (Werner, 2017b). This is because they share the idea of if the public role is needed to finance economically challenging projects, then local governments must own the companies, rather than subsidise them to allow them to exert control, achieve long-term cost benefits and ensures that benefits stay within the community (Herraras Martinez et al., 2023). Thus, loans for DH projects are typically provided by large utility companies and large financial institutions, including the EIB which recently signed a €30 million agreement with Asper Investment Management for the construction of new district heating networks and the refurbishment of existing projects in various municipalities in the country (EIB, 2020; Ramboll, 2022). Moreover, two of the country's largest private DH companies (Vattenfall and Eneco) have foreign shareholders (Herreras Martinez et al., 2023). This has contributed to the limited experience that most financial institutions in the country have about DH projects, resulting in requirements for a higher interest rate, and thus, reducing the financial viability of the projects (Ramboll, 2022).

The UK government has actively introduced some support mechanisms to encourage public, private, and third sector organizations to develop and improve DH network such as the Renewables Heat Incentive (RHI), the Heat Networks Investment Project (HNIP), and the Green Heat Network Fund (Ofgem, 2016). The European Regional Development Fund of the EU has also been provided to public and private bodies (EU, n.a.). However, since this fund is only available for EU regions, due to Brexit no investment for the 2021–2027 period is currently being made in the UK, but there are some ongoing projects for the 2014–2020 period (Ofgem, 2016). Private funding opportunities are also available in the UK, including corporate investment (equity) and loans and grants from commercial or non-commercial banks, but the immature DH market makes interest rates a barrier to access funding (Chalmers, 2023).

The implementation of high taxes on gas, oil, and electricity, but exemption on biomass further drove the development of the sector in Denmark and Sweden, especially regarding CHP systems (see Fig. 1) (Collier, 2018; Danish Energy Agency, 2017; Government Offices of Sweden, 2021). While, although the Netherlands have a high and gradually increasing gas tax, while reducing taxes on electricity,[12] and the UK has applied the same (low) tax on gas and biomass (5 %), the abundance, familiarity, affordability, and preference for gas as their energy source contributed to its dominance (Sahni et al., 2017).

Moreover, despite the UK having effective policies for renewables for electricity, relying mostly on incentives for market-based production for large-scale decarbonisation, heat has not received similar support (BEIS, 2020). Policies such as the RHI and HNI Project, have shown slow progress and failed to deliver the expected outcome (BEIS, 2020; Ofgem, 2016). This again shows the scale of the challenge in decarbonising a heating supply highly dependent on natural gas, as explained by an expert from the ADE (June 2022):

> *"The primary challenge for expanding heat networks in Britain is that both the general population and politicians are usually not very familiar with what heat networks are and how they work. So, a lot of the things we*

[12] Interview Eneco, May 2022

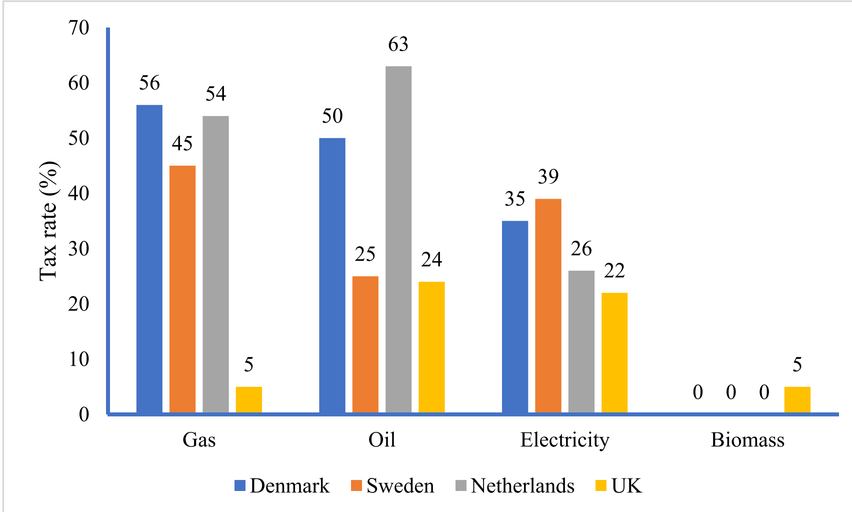

Fig. 1. Tax rates on energy sources.
(Source: adapted from Kerr and Winskel, 2021)

must do is primarily a mission of education so that both people and politicians can be comfortable with heat networks".

Gross and Hanna (2019, p. 363) argue that "more coordinated policies to improve technical standards and enhance the marketing and promotion of DH could help to address low consumer awareness and raise the credibility of these technologies, thereby creating adaptive expectations". The CCC (2023, p. 15) add that "there is long overdue need to empower and inform people to make green choices through a better understanding of how they can play their part and the implementation of policies that both make low-carbon choices easy, attractive, and affordable". As supported by Unruh (2000), evidence shows how path dependence, and the political-economy of heating systems lead to persistent market and policy failures that can lock-in fossil fuel-based infrastructure and lock-out the diffusion and adoption of low-carbon technologies such as DH despite their socio-economic and environmental benefits. Thus, it is of foremost need to have in place strict and targeted policy measures and implementation process to overcome lock-in and reduce barriers to and encourage adoption of new technologies such as regulatory framework, incentives, and dissemination of information.

4.3. *Energy efficiency of the built environment*

Energy efficiency of buildings has also been an important part of energy policy in Denmark and Sweden aiming to reduce energy consumption and increase the sustainability and security of energy supply (Collier, 2018; Danish Energy Agency, 2022). Sweden's strong building codes on energy performance, in place since the 70 s,[13] have led the country to have the most efficient buildings in the European Union (Collier, 2018). However, high energy-efficiency together with low electricity prices has stagnated their DH sector due to the decline in heat demand and market saturation and has eroded the business case for some DH investments (Collier, 2018; Magnusson, 2012). The lack of high urbanization growth and competition with HP also made it harder to further expand DH.[14] Nonetheless, Sweden pledged to be 50 % more energy efficient in 2030 compared to 2005, while Denmark plans a further reduction of up to 35 % of heating demand by 2050 (Petronen et al., 2017).

The UK and Netherlands introduced in 2007 and 2008, respectively, the Energy Performance Certificate (EPC) system, which shows how energy-efficient homes are and suggests possible energy-saving measures (Government of the Netherlands, 2022b; Sahni et al., 2017). The Dutch government further introduced in late 2016 a three-year 'Save Energy Now' campaign to encourage people to make their homes more energy-efficient through measures such as insulation and high-efficiency glass, with certain measures eligible for a grant or low-interest (tax-deductible) loan of up to €25,000 (Government of the Netherlands, 2022a). However, currently, some DH consumers from apartment buildings do not have incentives to save energy as their buildings' old joint heat distribution system (from 20 to 30 years ago) makes them unable to measure and control their consumption and results in a fixed fee charge for every apartment in the building.[15]

Such a lack of incentives demonstrates the need to have a complete incentive package that also involves the creation of the necessary technical and legislative conditions to allow consumers to reduce their energy use. This includes mandating the upgrade of heating distribution systems to individual smart metering and billing systems, especially in apartment buildings owned by a single landlord, to allow consumers to control, manage and pay for their own consumption, as well as to better control the availability and use of heat, and the flow temperature. The latter is also important to manage costs as lower temperatures also lower heating costs, and thus, helps to save consumers' money. It also brings benefits to DH companies such as lower heat losses and a longer lifetime of pipes (Diget, 2019). Thus, a Danish DH company (Viborg) is incentivising customers to lower temperatures through a motivation tariff that gives customers a discount for their actions (Diget, 2019).

In contrast, UK buildings are amongst the least energy-efficient in Europe as the country still lacks retrofitting support schemes (Collier, 2018). This constitutes an obstacle to the uptake of some low-carbon heat technologies with lower flow temperatures due to reduced efficiency of the technologies and increased heat demand (Sahni et al., 2017). The government's insufficient attention to efficiency improvements and demand management over technology could lead to a higher risk of failure of net zero emissions and to energy insecurity in the UK (Climate Change Committee – CCC, 2022). Inefficient UK homes have resulted in high heat losses, high energy demand to compensate for the losses and consequently high energy bills. This together with insufficient household income has led to around 6 millions (17.75 %) of UK households in fuel poverty (Hinson et al., 2024).

[13] Interview Swedish Energy Agency, April 2022
[14] Interview Swedish Council for DH, May 2022
[15] Interview PBL, April 2022

4.4. Market structure

DH ownership structures have also played a significant role in its development (Werner, 2017b). Denmark and Sweden have experienced substantial changes in DH ownership model over the last decades, but municipalities have been the most common owners, especially at the implementation stage, since they have the 'exclusive' practice of applying designated municipality taxes for financing their responsibilities and they own large housing companies, and thus were able to take long-term financial risks (Werner, 2017a). Currently, Danish municipalities and consumer-owned cooperatives own smaller DH systems in urban and rural areas, respectively, while large energy companies own the largest systems (Danish Energy Agency, 2017; Sovacool and Martiskainen, 2020). Experts interviewed pointed out the consumer-owned DH business model as one of the main reasons for the Danish DH success since consumers feel very proud in having their own company, being able to run it, and have a vote on the companies' decisions and changes. The Municipality of Aalborg's expert (May 2022) added that "*because of consumer-owned DH, municipality-owned companies that have recently expanded to some smaller cities have increased their level of contact with and engagement of citizens associations, consumers representatives, or local ambassadors*".

Swedish municipalities were initially the country's DH owners, but the deregulation of the energy market in 1996, and the introduction of competition in production and sales opened space for third-party. Municipalities now own 51 % of DH, being the rest owned by private companies (41 %), and state-owned and cooperatives (Dzebo and Nykvist, 2017; Magnusson, 2016). Magnusson (2016) argues that the deregulation posed some risks, challenges, and insecurities for smaller municipal companies as they had to compete for customers that were previously part of their customer base and face the risks of not having a market for their service. Full private ownership can also pose risks to the municipality, regional or central government of losing their influence on utility's business decisions, unless they have a mandate to oversee issues such as price regulation (Zeman and Werner, 2004). On the other hand, it can also be advantageous as risk is transferred to private companies, which are in a better position to handle risk and to deliver capital-intensive projects (Zeman and Werner, 2004). Nonetheless, the Swedish DH Association (SDHA)[16] (founded in 1949) and the Swedish DH Board (established in 2008) coordinate the various ownership types (including knowledge sharing and quality assurance system for distribution pipes), and issues arising between DH companies and between companies and their customers regarding the terms and conditions, respectively (Swedish Energy Agency, 2015; Werner, 2017a).

Around 90 % of the Dutch DH systems are owned by private companies, and the remaining by small companies, associations of homeowners, housing associations, and municipally owned companies (BEIS, 2020; Donnellan et al., 2018). However, as the country plans to deploy DH, there are some ongoing discussions and disagreements about the ideal ownership structure between public and private ownership.[17] The government plans to have 51 % ownership to encourage people to switch to DH, arguing that public hands would mean that public interests such as affordability, security of supply, and sustainability could be better safeguarded (ACM, 2021; Pascoe, 2022). This discussion has led major private companies to consider halting the development of new DH schemes or the expansion of the existing ones fearing losing their control over the DH systems while remaining financially responsible for the systems (Pascoe, 2022). It has also raised questions on "whether municipalities have sufficient capacity, resources and necessary enforcement mechanisms to fulfil the new task" (Ramboll, 2022, p.4).

Public ownership has proven quite challenging in the UK since some local authorities are struggling to manage their energy companies, with eight companies losing around £114 million between 2016 and 2020 – three of them are now under liquidation and administration (Simmonds, 2019). This situation raises concerns about local authorities' mishandling of taxpayers' money and to what extent they can make risky commercial investments to deliver capital-intensive energy projects. Werner (2017b) argues that municipalities' poor financial status and lack of experience in energy have often prevented further development and appropriate use of existing infrastructures. We therefore see that municipal ownership structures, in particular, support the roll-out of DH, but that a pre-requisite is for municipalities to have the expertise and capacity to manage ownership of an energy supplier successfully.

4.5. Pricing mechanism

Tariffs for DH systems in the study countries vary according to the fuel used and the existing pricing regulation models. The models offer different levels of effectiveness and outcomes (see Table 3). The Danish 'non-profit principle' for price determination ensures that the heating price that consumers' pay is not more than the necessary costs related to the heating production and supply, including operation and maintenance (Danish Energy Agency, 2017), otherwise the profit made goes back to consumers.[18] According to the Municipality of Aalborg's expert (May 2022), "*the fact that Danish companies are non-profit organization is a very progressive way to see DH as an asset similar to freshwater*". Offering consumers protection is essential to push them into DH because they know that they're being pushed into a monopoly; thus, protection gives them some assurance that they will not be abused.[19] Whereas the inclusion of the depreciation of assets and financing costs in the heating price ensures companies' short- and long-term price sustainability (Danish Energy Agency, 2017) but does not incentivise them to be economically efficient as these costs are included into consumers' price terrace.[20] The Danish Utility Regulator (DUR) uses voluntary benchmarking and complaint processes to aid transparency and efficiency in price setting and supply conditions (Danish Energy Agency, 2017; Johansen and Werner, 2022). Yet, a DUR expert argued that the principle is also "*what is been holding back the possibility for having new DH companies or new owners of the existing companies*".[21].

In Sweden, the liberalised/unregulated pricing structure has led to a substantial price increase and differences in many cities (e.g., by over 50 % in Stockholm) with privately-owned DH prices being around 3 % higher than municipally-owned DH, raising consumers' questions, criticism, and mistrust of some DH companies and, to some extent, to the sector in general (Egüez, 2021; Magnusson, 2012). This has also led to increased customers' demands for third-party access (Magnusson, 2012) or re-regulation of DH to reduce the perceived advantage that private companies were taking of their natural monopoly, but without success as companies were quite successful in lobbying the politicians.[22] Yet, a Vattenfall expert (April 2022) explained that "*DH companies have now understood the need to have predictable and long-term prices, and not increase prices yearly that much in order to improve consumers' perception of DH as a solution that can provide stable prices as opposed to electricity-based solution*". This shows the importance of DH companies having effective, dynamic, and customer-centric business models to remain competitive, especially considering the growing market of HP.

Donnellan et al. (2018) state that the complete price deregulation tends to erode consumers' service and protections. Thus, similar to Denmark, Sweden and the Netherlands use voluntary pricing and regular price monitoring, with DH companies required to publish annual

[16] In 2016, the SDHA was merged with the national electricity supply and distribution association into Swedenergy (Werner, 2017a).

[17] Interview Cooperatie Energie Samen, May 2022

[18] Interview Municipality of Aalborg, May 2022

[19] Interview DDHA, April 2022

[20] Interview DUR, April 2022

[21] ibid

[22] Interview Swedish Energy Agency, April 2022

Table 3
Comparison of pricing mechanisms in the study countries (Source: adapted from BEIS, 2020; Collier, 2018; Danish Energy Agency, 2017 ;; Donnellan et al., 2018 ;; Egüez, 2021; Harmelink, 2017; Johansen and Werner, 2022; Magnusson, 2012).

Country	Type of regulation	Advantages	Disadvantages
Denmark	Non-profit principle	Consumers do not face indirect taxation or subsidisation through companies' services. Companies are not permitted to make a profit. Ensures that the final DH price for users is kept relatively low. Ensures the provision of high-quality service. High customer satisfaction. A very low level of customer complaints.	Does not incentivise companies to be economically efficient. Can discourage new companies or owners from entering the DH market.
Netherlands	No more than-otherwise principle	Price is kept at gas price cap.	Can discourage companies from entering the DH market and upgrading their existing systems. Can limit innovation. Can discourage consumers from connecting to DH. Can lead users to disconnect from DH network Can lead consumers to look for cheaper alternatives.
Sweden	Deregulated	DH pricing structure changed from cost-recovery basis to market prices. Transparency has been effective to motivate DH companies to lower their prices. Transparency has helped users better understand and predict their bills, and plan for price changes. Transparency has increases users' confidence in DH.	Substantial increases and differences in DH prices. Price increases have raised consumers' questions, criticism, and mistrust of some DH companies and the sector. Deregulation erodes consumers' service and protections.
UK	Unregulated	No price cap to DH companies.	Consumers have less protection and security than those using gas and electricity. Can discourage consumers from remaining connected or to be connected to DH.

reports for prices comparison and to justify the sustainability and any differences between categories of customers (Donnellan et al., 2018; Harmelink, 2017). Sweden also uses complaints and mediation processes (BEIS, 2020). IRENA et al. (2020) argue that policies to regulate the natural monopoly (e.g., oversight of competition, price transparency or regulation) can improve users' confidence in DH systems.

The Netherlands uses the 'no more than-otherwise principle' pricing mechanism to base on gas price the maximum price (annually published by the government[23]) that DH customers pay (Authority for Consumers and Markets – ACM, 2015). However, there is low transparency in price setting since DH companies are not obliged to reveal their real operation costs, and there is a lack of knowledge sharing and best practices within project design (Ramboll, 2022). Moreover, such price cap makes DH a dearer, and non-price competitive and effective alternative to fossil fuel-based heating to consumers. This can discourage consumers from connecting or remaining connected to DH, and companies from entering the DH market and upgrading their existing systems and limit innovation for allowing prices to be kept at cap level even if actual costs are well below the cap (Donnellan et al., 2018). Indeed, according to a PBL's expert (April 2022), "*the rapid increase of gas prices gave to some DH companies the opportunity to also increase their prices, and some of them used the maximum cap, while others stayed way below the maximum levels since they only strive for a fair, not the maximum profit*". Nonetheless, as the country phases out gas extraction and supply, and gradually increases gas price, it became unsustainable to maintain the gas price as the reference point (Lavrijssen and Vitéz, 2021). Thus, a new price regulation is underway to transition to a cost-plus cost-based price structure.[24]

In the UK, the lack of DH regulator, price regulation or cap[25] means that DH consumers have less protection and security than those using gas and electricity (regulated by Ofgem). The Heat Trust, an independent, non-profit consumer champion organisation, is currently performing some voluntary DH regulation, including consumer protection; but this only covers around 12 % of consumers (BEIS, 2021b). Nevertheless, the government appointed Ofgem to start, from 2025, supervising, capping or regulating prices and profits where there is little or no competitive pressure that would otherwise keep prices down (BEIS, 2020). Ofgem is also expected to protect consumers on transparency and quality of service (BEIS, 2021b).

However, the unsustainable and unjust Ofgem energy price cap applied during the energy crisis (between 2021 and 2023 - £3549) and the quarterly updates call for Ofgem to revisit its price regulation model and approach to improve transparency, and maximise market efficiency, consumers' protection, and trust, while also addressing energy equity and justice concerns. The Danish price setting principle and the Swedish price transparency system can offer some useful regulatory lessons of emerging DH markets in a sustainable, just, and transparent manner, which could then be adjusted and aligned to UK conditions.

5. Conclusions

This research collected valuable and distinct lessons from the different and successful pathways that Denmark and Sweden took for DH development, which rendered them an almost saturated urban market. These countries have currently shifted their focused to improving the efficiency and decarbonising the existing DH systems. The UK and the Netherlands can follow and adapt these unique lessons to increase the share of low-carbon DH into their heating system, and to ensure the supply of secure, sustainable, and affordable heating sources, particularly considering the gas price instability and volatility. The low penetration of DH in these countries might facilitate the expansion of low-carbon DH since building it from scratch is easier than retrofitting it to existing systems.

Denmark and Sweden have successfully used the same strategy in the past to respond to the gas supply shortage and ensure their energy security, and this model could be emulated. Towns and city centres offer great opportunities as the greater concentration of multi-storey buildings will enable more properties to be connected per km of pipes and

[23] Interview ACM, May 2022
[24] Interview ACM, May 2022
[25] Interview ADE, June 2022

thus reduce investment and supply costs and increasing the viability of the project. However, attention should be paid to the need to have an effective enforcement body, with the necessary power to mandate connection and to the need to improve the energy efficiency of buildings to increase the efficiency of the technology and reduce heat loss and energy consumption.

We recognise that the development of the right policies, regulations, and measures such as technical standards and financial incentives is important to ensure the expansion and upgrade of DH. However, as seen in Sweden and corroborated by Sovacool et al. (2021), due to the political-economy and path dependence of the heating sector and familiarity with and preference for fossil fuels, it is crucial that governments create appropriate conditions, provide more support, and speed up actions to lock-out fossil fuel-based infrastructure and lock-in the diffusion and adoption of low-carbon DH. There is a certain paradox in this finding: the greater the potential for DH to expand, the greater the existing path-dependent barriers that need to be overcome.

Governments must enhance the role of DH, educate, encourage the adoption, and involve people, politicians, and other key stakeholders (e.g., building owners, property developers, heat suppliers, funding providers) in the timely transition to and expansion of DH. They must also address the current insufficient financial means and institutional capacity and skills as well as materials shortages for DH infrastructure design, planning, development, operations, and uptake. If the alternative is available, known, and cheaper than their current sources, especially considering that people are currently facing high energy prices and are looking for ways to reduce their energy consumption and bills, people can easily switch to DH, and this could also lead to the government increasing its DH ambitions.

Results show that the presence of a DH regulator is crucial for a functioning market and the development of the systems. As seen in Sweden, deregulated markets are difficult to control, they require exceptional and innovative protective measures to increase clarity in price setting and to maintain prices at just and sustainable levels for both consumers and businesses. The price setting measures implemented in all the study countries do not seem to have the desired balance, but they can serve as lessons to those laggard countries to improve their regulatory transparency, performance, market function and efficiency, supply conditions (including the right to disconnect from DH), and consumers' protection and trust. If this balance is not achieved, the business case for DH can be eroded since some customers may choose to disconnect from DH towards other technologies perceived as being more affordable or flexible (easy to control/manage individually) such as HPs, which already represent a competition to DH. Thus, the development of new business models, and more research and innovation are needed to improve the business case, cost-effectiveness, and efficiency of DH, including the reduction of investment costs related to the deployment of 5GHD.

CRediT authorship contribution statement

Ed Turner: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition. **Ying Miao:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition. **Daniela Salite:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization.

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.

Data availability

Data will be made available on request.

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