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From consumers to pioneers: insights from thermal energy communities in Denmark, Germany and the Netherlands

Sara Herreras Martínez[1*], Justus Mesman[2], Daniel Møller Sneum[3,4], Lars Holstenkamp[5,6], Robert Harmsen[1], Marijke Menkveld[7], Sanne Akerboom[1] and André Faaij[1,7]

Abstract

Background While energy communities working on electricity provision have been extensively studied, thermal energy communities (TECs) focusing on bringing district heating (DH) systems to decarbonise heat systems in buildings have been relatively under-researched. This study addresses this gap by presenting the first comprehensive examination of key factors influencing the emergence and development of TEC projects in Denmark, Germany, and the Netherlands. The study uses an established analytical framework from previous research encompassing seven dimensions: market structure, hard- and soft institutions, financing, physical infrastructure, capacity, and interactions with other stakeholders. Data are gathered through a literature review and interviews.

Results TECs have emerged at different times in each country, shaped by contextual circumstances and diverse forms of institutional support. Elements that have supported the development of TECs are regulatory frameworks promoting DH growth, heat decarbonisation policies, economic incentives to use waste heat in plants, targeted financing mechanisms, and assistance to enhance the capacity of TECs. External factors such as high oil prices, seismic events, and recent rising energy prices have also spurred project initiation. TECs also rely on additional factors for success, including organisational and entrepreneurial abilities to engage with stakeholders, gain social acceptance, and secure commitment from community members. Involvement from local government, intermediary organisations, and private companies is crucial for TEC implementation.

Among the studied countries, Danish TECs stand out as the most developed, benefiting from a stable policy environment, decades of experience with DH and TEC, and positive societal perceptions. Conversely, Dutch and German TECs face challenges because of the early stage of their heat transition, dealing with financial obstacles, underdeveloped policies, unfamiliarity with DH technology and with TECs, as well as the need for expensive infrastructure changes. Shared challenges across regions include capacity limitations in small projects and implementing cost-effective, local, and sustainable heat sources.

Conclusions In light of the study's findings, policymakers must consider establishing stable, integral and flexible policies supporting heat decarbonisation and TECs, addressing TECs' reliance on limited capacities, involving TECs in local heat municipal plans, and facilitating high DH connection rates where DH is the most cost-effective solution from a socio-economic perspective.

*Correspondence:
Sara Herreras Martínez
saraherreras@gmail.com
Full list of author information is available at the end of the article

Background

The European Union (EU) envisions that active and cooperative engagement of citizens through renewable energy communities (RECs) is a crucial element for a successful energy transition [1, 2]. The concept of RECs was adopted in European legislation in 2019 with the *Clean Energy for All Europeans Package,* which officially recognised and established new rights to enable community energy generation, consumption, storage and trading [1]. The recast Renewable Energy Directive (RED II), part of the Clean Energy Package, includes specific provisions for Member States to provide favourable conditions for developing RECs, such as simplified administrative procedures and access to financing [3]. Today, European RECs reach roughly 4,000 initiatives[1] [4, 5] and have a significant growth potential [6].

This research defines RECs in a broader sense, acknowledging that many existing RECs (established before RED II) may not fully comply with all RED II criteria. Therefore, this paper defines RECs as decentralised, autonomous and democratically organised entities controlled by their members, including citizens (the focus of this research), businesses and local governments [7, 8]. RECs manage activities along the energy value chain, from production to distribution and energy demand services [9]. They operate non-commercially and combine economic, social and environmental community goals [10]. RECs have similar ambitions as local governments in fostering low-carbon energy transitions at the local level. Besides, RECs are of high added value to local energy plans because they are usually early adopters of renewable systems and can foster citizen engagement [11]. The latter is essential, as the absence of community participation can impede the progress of renewable energy projects [12, 13].

Research gap and goal

RECs have received considerable scientific attention in recent years. Numerous studies can be found on the benefits RECs bring as well as on the motivations and contextual factors playing a role in the successful establishment of such initiatives—e.g., Koraila et al. [14]; Brummer [15]; Lowitzsch [16]; van der Schoor and Scholtens [17]; van Lunenburg, Geuijen and Meijer [18]; Busch et al. [19]. However, most of the literature focuses on RECs engaging in electricity-related projects such as wind and solar. RECs focusing on heat provision in residential buildings to jointly generate and consume heat (hereafter thermal energy communities or TECs[2]) have been under-researched, as noted earlier in literature [20–22]. One potential reason is that fewer initiatives are involved in heat production than in electricity and energy-saving projects [23]. Moreover, despite the need to switch to sustainable heating supply in buildings (hereafter "the heat transition"), the EU lacks a unified strategy for heat decarbonisation, compared to the electricity sector. This is partially attributed to the complexity and localised nature of the heat sector [24]. The local focus of heat projects also makes studies case- and country-specific and thus potentially less appealing to the international audience [22].

Nevertheless, the heat transition is an essential and challenging milestone in achieving European climate targets [25]. Heating in buildings represents 42% of all final energy use, but it is primarily dominated by fossil fuel-based systems [26]. As EU member states develop support frameworks for community initiatives under RED II, they face a dual challenge in the heat transition: a limited TEC experience in most countries and an inadequate information base. Prior research has either assessed only selected aspects, such as financing and capacity problems in TEC projects [27, 28], or has focused on one specific country [22, 29]. Although there are a few cross-country analyses [30, 31], these fail to provide a comprehensive understanding of a wide range of factors influencing TEC initiatives. Therefore, this research aims to tackle this gap by comparing crucial factors hampering or fostering the emergence and development of these initiatives in three countries. The three-country comparison enables us to extract insights that have broader applicability than individual case studies. This approach allows the identification of valuable factors to integrate into policy frameworks supporting TEC implementation across Europe.

The research focuses on TECs owning a local district heating (DH) system. DH systems efficiently provide thermal energy (e.g., from waste heat, solar thermal, geothermal, biomass or fossil fuels) to a network of buildings, including residential, commercial, and industrial users [32]. Developing and realising a DH system is complex and requires a different approach than cooperative electricity projects:

[1] The exact number may vary depending on the definition of energy cooperatives and energy communities and the criteria used to count them. For instance, Wierling et al. [214] counted more than 10,000 energy communities for the European Union.

[2] TECs can also be found in literature as heat cooperatives and district heating cooperatives. The term TECs is used in this paper as earlier applied by Fouladvand, Ghorbany et al. [20]. The authors defined TECs as a system where "*households collectively invest in renewable thermal energy systems (e.g. geothermal, bioenergy, heat pumps or solar thermal) to jointly generate and consume thermal energy.*"

- Homes and areas must be physically connected, not just administratively, requiring a significant change in the basic grid infrastructure [23].
- The success and viability of a DH project depend on the commitment of most residents within an area. For example, Danish project feasibility thresholds are around 70% connection rate [33]. Hence, higher levels of community engagement are needed, focusing on potential customers within a smaller area rather than the wider community [22, 28].
- DH networks function as a local natural monopoly, unlike individual heating systems and electricity provision. Without competition, consumers cannot switch between providers, and without appropriate regulation, they might be exposed to high prices [34].
- The investment to participate in a cooperative DH project can be significantly larger and less lucrative than in other energy activities [8, 35, 36].

Considering the substantial technical potential of DH in Europe [37], TECs can help achieve European sustainability goals and DH adoption by fostering community participation, encouraging long-term affordable prices, and ensuring revenues stay within the community [38].

Denmark, Germany, and the Netherlands were selected as case studies. The three countries have committed to ambitious goals in the heat transition (see The heat transition) and have many RECs with solid cultural norms regarding the cooperative model[3] and local energy activism [5, 39, 40]. However, they have varying degrees of TEC growth. Denmark is the world front-runner in deployed TECs [41] and is seen as a model to emulate within the TEC sector arising in other countries [30, 38, 42]. In Germany, one in three newly founded German RECs operates a local DH network [35], but TECs have a small market share and still encounter numerous problems [22, 43, 44]. The Netherlands has only a handful of operational TECs with many initiatives under development [45], although these face numerous challenges [28, 46–48]. The diverse contextual factors that shape the emergence and development of TECs in each country justify a more thorough investigation. The following research question guides this study:

What framework conditions influence the emergence and development of TECs in Denmark, Germany, and the Netherlands, and to what extent do these pose a barrier or a strength?

[3] As defined by Lowitzsch and Hanke [215], p.140 "*Cooperatives are autonomous associations with open membership and the purpose to support the economic, cultural or social activity of their members through commonly owned or collective business operation*".

The paper is organised as follows. The heat decarbonisation goals and the surge of RECs and TECs in the countries studied are discussed (The heat transition), followed by the Methods and the Results of the cross-country comparison. Finally, based on the comparative analysis, the article discusses the key outcomes (Discussion) and provides a summary and policy recommendations to foster TEC development (Conclusions).

Denmark, Germany and the Netherlands as case studies

The heat transition

The selected countries have different starting points in the path to decarbonising heat systems in buildings, and they have committed to a transition away from fossil fuel-based systems, albeit with various timelines and measures (Table 1). The challenge is larger in Germany and the Netherlands than in Denmark, as their share of renewable heat is far below the national targets. The initial objective in all three countries is to achieve heat decarbonisation in new buildings (Table 1). Fossil fuel bans in existing buildings are currently only implemented in Danish regulations. However, in Germany and the Netherlands, to-be-installed heat systems will be required, step by step, to use more sustainable sources from 2026 onwards (Table 1).

DH plays a vital role in the decarbonisation strategies of the three countries [49], and it is the preferred system among TECs. In Denmark, DH is the dominant heat system in households, and TECs play a large role [50]. In the Netherlands, 68% of the TEC's projects under development include DH systems [45]. DH is also the technology most used in German TECs [4, 51].

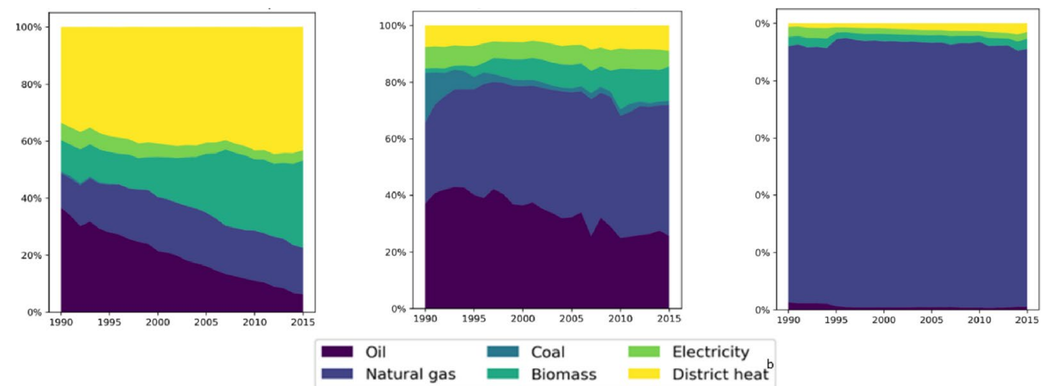
The emergence of RECs and TECs

The surge and historical evolution of RECs in Denmark, Germany and the Netherlands has been the focus of numerous studies [39, 63, 66, 67]. Energy communities are not new phenomena and existed before the energy transition started. In Denmark and Germany, cooperatives have been historically important in remote areas and islands where fuel accessibility and infrastructure were lacking [1, 63].

In the 1970s, grassroots movements emerged in response to the oil crisis in the three countries and were stimulated by anti-nuclear sentiments [63, 68, 70]. RECs were created as alternative economies to shift away from fossil fuels and improve community well-being, emphasising collective self-reliance and mutual assistance [8]. These first RECs focused on electricity production, except in Denmark, where DH and wind cooperatives have historically held a central position [39]. In Germany and the Netherlands, cooperative wind projects were

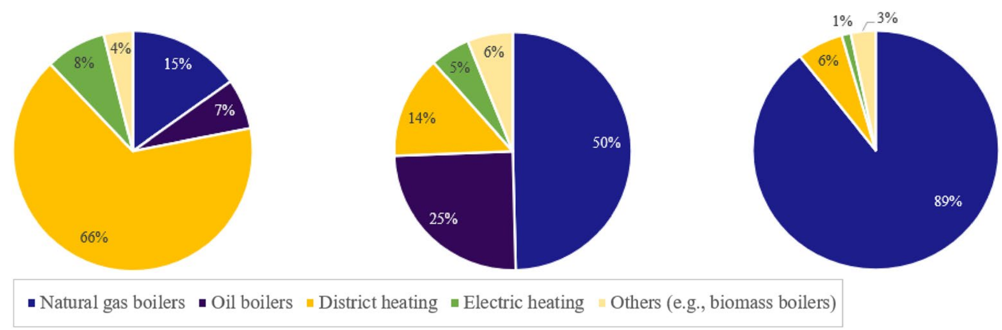
Table 1 Fuel mix for residential heating and heat decarbonisation targets and measures in the countries studied

Fuel mix of residential heating consumption 1990–2015 (%)[a]



[b] Share of renewables in district heating (2019): Denmark (62%), Germany (22%) and the Netherlands (23%)

Share of technologies in residential heat in 2019[c]



	Denmark	Germany	The Netherlands
Share of renewables in final heat and cooling demand in 2019 (%)[d]	69	14	13
Target year of heat decarbonisation[d]	2035 (no natural gas heating in buildings; oil boilers can remain) 2030 (carbon neutrality for DH and electricity-based systems)	2045 (all buildings) 2030 (interim target to have 50% of heating with renewables)	2050 (all buildings) 2030 (interim target to decarbonise 20% of all buildings)
Existing bans on fossil fuel heat (as of June 2023)[e]	Oil and natural gas heating in new buildings (since 2013). Oil is prohibited in areas with natural gas and DH (since 2016). No longer mandatory use of natural gas in DH plants (since 2018)	At least 15% share of renewable heat in new buildings (since 2009)	Natural gas heating in new buildings (since 2018)

Table 1 (continued)

	Denmark	Germany	The Netherlands
Planned bans on fossil fuel heat [e]	In 2035, no natural gas heating in all buildings	From 2026–2028 onwards (the start year depends on the number of inhabitants per municipality), at least 65% share of renewable heat in to-be-installed heating systems in existing buildings. In new buildings, the rule starts in 2024	From 2026 onwards, a requirement that to-be-installed heating systems in existing buildings must run largely on sustainable sources—e.g., (hybrid) heat pump*, DH. No new natural gas boilers From 2024 onwards, municipalities will have the legal power to terminate natural gas supply in districts

[a] Figures from [52]

[b] Data from [53]

[c] Own figures with data from [54–56]. For Germany and Denmark, 2020 data are used. For the Netherlands, only 2019 data are available

[d] Share includes buildings and industry. Data from [57–59]

[e] Data from [59–62]

* A hybrid heat pump runs on electricity (the heat pump unit) for most of the year. It includes a backup heating source (i.e., a gas boiler) that is activated during very cold weather conditions when the heat pump alone does not provide sufficient warmth

among the earliest, followed by solar initiatives [9, 69, 71].

Denmark pioneered the establishment of TECs in the early years [64], expanding notably between 1950 and 1985 (Fig. 1). Today, Danish TECs are the most developed and numerous among the three countries. The data shown in Fig. 1 for 2022 translate into a share of 5.5% per 100,000 inhabitants for Denmark compared to 0.24% in Germany and 0.02% in the Netherlands. In Germany and the Netherlands, TECs have primarily emerged in the past 10–20 years. The number of German and, in particular, Dutch TECs is far below the number of RECs, where wind and solar projects account for a significant part (Fig. 1).

A deeper explanation concerning the origins of the TEC sector in each country is provided in the section Market structure.

Methods

The research employed qualitative methods to examine the context in which TECs operate in the three contexts. To identify critical factors influencing the development of TECs, our study is based on literature on innovation studies and sustainability transitions. In particular, our study used a framework developed by Negro, Alkemade and Hekkert [76], which is based on a literature on technological innovation systems where obstacles at the system level were systematically studied. Negro, Alkemade and Hekkert [76] conducted a literature review of 50 studies analysing the factors around the development and diffusion trajectories of various renewable energy technologies across different European countries. These are referred to as systemic problems, which are defined as "*all systemic factors that block the operation and development of innovation systems*" [76]. The literature review resulted in a theoretical typology of typical systemic problems in developing and diffusing renewable energy systems.

The speed, direction, and success of RECs/TECs can be compared to the development of renewable energy systems and the literature on technical innovation systems as they are strongly influenced by the environment in which they develop [64, 77, 78]. Thus, energy community initiatives can be interpreted as niche innovation in an early stage of development and the outcome of interactions between the political system, consumers, producers, the supply system, and the infrastructure, among other factors [79].

Our study aims to examine the factors that impact the deployment of TECs. A review of the literature on RECs and TECs has identified several critical factors supporting or hampering the development of these community initiatives, including a lack of professionalism, unstable or insufficient policy support, limited access to capital, and challenges in community engagement [15, 19, 22, 31, 68, 80–82]. Given that the Negro, Alkemade and Hekkert's framework addresses all these factors, we have chosen to employ it in our research. The framework has also proven to be effective in studying and comparing the deployment of RECs in various contexts [77], as the present study aims to do. In short,

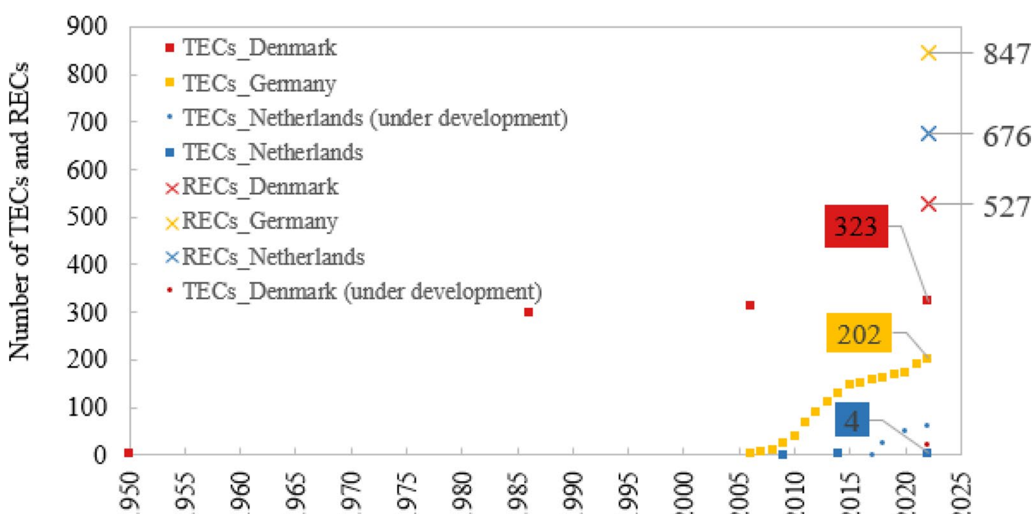


Fig. 1 Evolution of TECs over time and number of RECs in 2022 in the countries studied. Own figure using data from Denmark [5, 70, 72, 73], Germany [5, 74] and the Netherlands [5, 75]. Note that the number of German TECs in 2021 has been estimated at 291 by another study [31], but here, the German Renewable Energy Agency figures are presented as they provide historical data. No data could be found for the German TECs under development

this framework has been chosen for its comprehensiveness and flexibility, as it can be applied in different settings.

Table 2 shows the seven dimensions of the framework: the market structure, hard- and soft institutions, financial infrastructure, physical infrastructure, capacities and interactions. The Negro, Alkemade and Hekkert's framework [76] included an additional category called "knowledge infrastructure", referring to the gap between knowledge produced at universities and what is needed in practice. Our study excluded this category because previous studies have not underscored the knowledge gap between university research and the needs of TECs as critical for REC/TEC deployment, while all the other dimensions of the framework have been identified as critical [15, 19, 68, 80–84].

To tailor the framework for our study, we integrated additional definitions and sub-categories relevant to the study of TECs (second and third columns of Table 2). For example, the themes '*Market structure*', '*Hard institutions*' and '*Soft institutions*' combine aspects related to DH projects and TECs. The '*Physical infrastructure*' focuses on the main difference observed between TECs in the three countries, i.e., heat source selection and the presence of grid-based heating. The theme '*Interactions*' was split into three categories reflecting the most critical actors working with TECs. Last, we have expanded the application of the framework earlier employed by Mignon and Rüdinger [77] and Negro, Alkemade and Hekkert [76] beyond identifying barriers to pinpoint also strengths and replicable lessons.

Data on systemic factors per country were first collected via a structured literature review drawing from various sources (e.g., peer-reviewed journals, book chapters, reports, policy documents and websites of TECs). Search queries included terms such as "thermal energy community", "heat citizens cooperatives", "district heating community projects", "heat cooperatives" and "renewable heat communities". These terms were combined with country-specific queries and queries linked to the analytical framework, such as "district heating regulation", "financing in heat/energy community projects", "heat sources in renewable heat/energy communities", and "partnerships in heat/energy community projects". The search mainly included sources in English, but Danish, German, and Dutch literature was also used.

Open-source data reflecting key figures of TECs as a sector (so not case-specific) are scarce. If such data were not available, figures for RECs, the DH sector, or, in the case of Germany, bioenergy villages were used instead. The authors acknowledge the potential uncertainties inherent in using a broader (RECs, DH) or smaller (bioenergy villages) dataset for investigating TECs. Therefore, the data collected through literature were checked and refined by conducting semi-structured interviews. Twenty-nine interviews were conducted with various stakeholders, including members of ten TECs, researchers, topic experts and representatives of umbrella energy

Table 2 Categorisation of the theoretical systemic factors developed by Negro et al. [76], the definition applied, and the data collected in this paper

Category	Definition	Data collected
Market structure	Organisation and structure of the market in which the TECs operate	• Historical facts explaining the current DH and TEC sectors • Current TEC market share in the DH market • Dominant actors and technologies co-existing with TECs
Hard institutions	Formal rules within the institutional context, such as national regulations and support instruments for heat decarbonisation and TECs	• National regulation and support instruments applicable for DH and heat projects • National regulation and support instruments applicable for TECs/cooperatives
Soft institutions	Social perceptions and acceptance that may hinder or support the development of DH projects and TECs	• Social acceptance and trust for TECs, DH systems and for switching heat systems
Financial infrastructure	Financing mechanisms used by TECs to acquire capital in TECs	• Available subsidies, loans, guarantees and other financial instruments to finance the pre-development, development and realisation phases • Accessibility of these instruments to TECs
Physical infrastructure	Technical structures required for the project to function	• Presence of collective heat infrastructure • Heat sources used
Capacity	Availability of expertise (knowledge) and human resources (workforce)	• Human capital and expertise available in TEC projects
Interactions	Functioning of interactions between the TECs and other key actors	• Role and support local and regional governments • Role and support private sector (e.g., consultants, project developers) • Role and support intermediaries

cooperatives (see Additional file 1) Interviews lasted between 60 and 90 min.

An interview guide was developed in line with the analytical framework (see Additional file 2). Questions were tailored per interview to fit the specific purpose of each interview. The authors also conducted participatory observation about cooperative heat in Denmark and the Netherlands at a meeting organised by a Dutch intermediary organisation. The timeframe of the data collection ran from April 2022 to December 2023. Interviews were transcribed, and a deductive and inductive analysis was conducted. The deductive part followed the existing framework to create categories and codes for data analysis. Additional sub-themes were generated inductively by exploring the data. The gathered data were added to a database, coupling these to the various categories of systemic factors and allowing the allocation of barriers, strengths, similarities and differences.

Results

Results are presented following the structure of the analytical framework. The format (INT-number interviewee) is used when referring to interview data. The corresponding interviewee numbers can be found in Additional file 1

Market structure

The three countries have distinct DH market structures in which TECs operate, with Denmark being the only country where TECs have a notable market position (Table 3). As explained below, the differences in today's market structures, developed over decades, stem from divergent political and regulatory choices, socio-economic developments and the availability of domestic heat resources.

The solid Danish TEC sector can be attributed to historic energy-security concerns, cooperative traditions, and a favourable policy environment that promotes non-profit/consumer-oriented rules in DH. While DH has existed in Denmark since 1903 with combined heat and power (CHP) plants owned by municipalities, TECs emerged in the 1950s and accelerated between the 1960s and 1980s [70, 73] (INT-27). The tradition of cooperative ownership, rooted in the agricultural and electricity sectors, transitioned to the DH sector (INT-17, INT-27). This transition was later incentivised by environmental movements and a need to ensure a stable local heat supply during the 1970s oil crises [65, 72].

At that time, Danish households heavily relied on imported oil for individual boilers [85]. The discovery of domestic natural gas reserves in the North Sea and the potential for DH expansion offered a much cheaper, cleaner and more comfortable alternative [65, 86, 87]. DH gained popularity over the years due to its energy efficiency. Using surplus heat from industrial processes and power generation in DH systems was seen as a cost-effective and environmentally friendly way to provide heating to urban areas [65].

The introduction of the Danish Electricity Act and the Heat Act in the late 1970s (Hard institutions) spurred the expansion of DH and CHP plants and allowed a high degree of consumer control in DH companies. Today, 64% of Danish households are served by DH, much higher than the German and Dutch share (Table 3). TECs hold an important market segment in

Table 3 Overview of the market structure and TEC characteristics in the countries studied

	Denmark	Germany	The Netherlands
Share of DH in heat provision[a]	66% of households connected to DH	14% of households connected to DH	6% of households connected to DH
Share of TECs in the market[b]	In terms of the number of DH networks: 84% TECs, 13% municipal, 3% private In terms of total heat supplied, TECs delivered 34% heat	In terms of households connected to DH networks: < 0.5% Most other DH systems are municipally owned	In terms of households connected to DH networks: < 0.01% Share division in terms of total DH supplied: 91% commercial companies, 5% public, 4% public–private
Typical TEC ownership and role in the DH chain[c]	Citizens organised as cooperatives are vertically integrated companies, typically owning the heat sources. In some cases, independent heat producers may provide heat to their DH grid	Citizens organised as cooperatives usually operate the DH network. They either buy the heat from local heat producers or own the heat generation facilities. The bioenergy village concept implies there is ≥ 50% local ownership of the production facilities and/or the DH network (local can include municipalities, local companies and residents)	Based on three operational projects: Citizens with private companies and/or the municipality have formed a vertically integrated company (TECs in Thermobello, Nagele and Traaise Energie Maatschappij). In other projects under development, independent heat producers also provide heat to the DH grid

Data sources: [a][55, 93, 94]

[b] [95, 96] and interview data

[c] [35, 48, 97–99] and interview data

the Danish DH sector. Nevertheless, they have only seen moderate growth in the past 35 years, with small cooperatives merging into larger DH companies in recent years (INT-27). While one interviewee noted that areas where DH is the most feasible alternative have already been developed (INT-23), 2021–2023 have seen record numbers of new DH consumers [88–90]. Recently, there has been a rising interest in the so-called "termonets" in communities that depend on gas and are unsuitable for conventional, large DH systems. These are very small TEC projects (e.g., a single road with a few houses) that use centralised ground heat sources in combination with heat pumps [91, 92].

So far, the energy transition in Germany and the Netherlands has been primarily an electricity transition [63, 100]. The first DH systems appeared in Germany at the end of the 1890s [101] and in the Netherlands in the 1920s [102]. However, today, DH systems have only a minimal share (Table 1). Individual gas- and oil boilers heat two-thirds of German homes, whereas in the Netherlands individual gas boilers heat about 90% of homes (Table 1). After the Second World War, West and East Germany adopted different policies to reconstruct their heating infrastructure, with socialism driving DH growth in East Germany [103, 104]. Since the Netherlands discovered large natural gas reserves in the province of Groningen in 1959, energy policies focused on developing decentralised heat systems that utilised this abundant domestic source, which also generated revenues for the Dutch state [64, 105]. German and Dutch municipalities, as in Denmark, built the first DH systems to enable efficient electricity production in CHP plants. Today, German municipalities and Dutch private companies own most DH systems, while TECs have a minimal market share (Table 3).

The first German TEC dates back to the foundation of the first bioenergy village ("*Bioenergiedörfer*") in Jühnde in 2006 [106, 107]. A bioenergy village is a local heat supply network in rural areas where thermal energy is transported via a water pipe system from a heat source to consumers [108]. By definition, a bioenergy village meets its electricity consumption and a minimum of half of its heating requirements through locally produced biomass [99]. After the first bioenergy village, many regions followed, with 180 projects today and many others under development [109, 110]. Numerous bioenergy villages emerged during a period of low grain and milk prices coupled with high oil prices [44]. Projects were often started by farmers operating biogas plants who, due to financial incentives, sought consumers to use their excess heat from electricity production (Hard institutions). The appeal of constructing biogas plants declined markedly due to changes in the feed-in tariffs implemented from 2012 onwards.

While Dutch cooperatives in other sectors, such as electricity, agriculture, and banking, are well-established, TECs are very scarce in the Netherlands [111]. Only four TECs are in operation, compared to 1,000 cooperative PV and 90 cooperative wind projects [45, 75]. Nevertheless, there has been growing interest in TECs over the past years. Since 2012, earthquakes from natural gas extraction in the Groningen region have played a role. This has driven important heat decarbonisation policies and increased social awareness of the importance of reducing natural gas dependency [112, 113]. Dutch municipalities were responsible for planning and executing local heat decarbonisation strategies by the end of 2021 [112]. Within a national knowledge-sharing programme that supported local heat decarbonisation pilots financially (known as the natural gas-free neighbourhoods program or PAW in Dutch), numerous TEC initiatives emerged—see Dutch TECs in Additional file 3) and the overview of all PAW pilots nationally [114]. In 2022, 60 TECs were at different stages of developing a DH project [45]. These projects are often in cities [45, 115], differing from many Danish and German initiatives, which are mainly based in rural regions and small villages where bioenergy heat sources, typically used by TECs, are available [41, 108].

Hard institutions

Numerous policies, either directly or indirectly, have shaped the landscape of the heating sector and TECs in the three countries. We examine historical and recent regulations (Table 4) and important regulatory reforms under development (Table 5). Additional file 4 provides a broad overview of additional policies over time. Denmark has benefitted from a long, stable, and robust regulation since the 1970s, favouring the continuous expansion of DH projects and the dominance of consumer- and municipality-owned companies. Although the position of TECs in heat-related regulation is a process under development In Germany and the Netherlands, both countries have adopted other policies that foster the emergence of these initiatives. Recent regulatory changes in Germany and the Netherlands replicate a few aspects of the Danish model, as explained below.

The design and stability of the Danish DH regulation The Danish Heat Supply Act, with its key elements (Table 4), has fostered a favourable environment for TECs, protecting customers and making DH a competitive and socially widely accepted technology [85]. A crucial rule explaining the position of TEC's is the non-profit principle, as the primary focus of TECsis not on making returns (like for example commercial companies), but on providing sustainable and low-cost heat

Table 4 Identified key policies in the research playing an important role in the development of TEC's and their position in the heat market in the countries studied

Denmark	Germany	The Netherlands
Heat Supply Act (1979) • *Tariff system* It establishes cost-reflective tariffs and transparency rules, and it prohibits companies from making profits [116], [117]. Profits must be returned to customers via tariff reductions or be reinvested in the project [118] • *Mandatory connection* (until 2019): Obligatory connection in predefined zones mitigated the risk of insufficient customer base, fostering investments and DH expansion [116] • *Consumer inclusiveness* The law stipulates that the majority of the board in DH distribution companies should be elected by consumers or municipalities [119]. A legal provision also grants consumers the first option to buy if a DH company is sold, although such sales are infrequent.[85] • *Stable local heat planning* Local authorities have long held the responsibility for heat planning, integrating local initiatives into municipal plans and approving projects [85] (INT-27). The Heat Act requires municipalities to collaborate with local utilities in heat planning [120]	*Reform in Cooperatives Act* (2006) • It eased the process of founding and running small cooperative projects [121], [122] (INT-24) *Feed in tariffs of the Renewable Energy Sources Act—EEG* (2000) • Feed-in tariffs for electricity generation were implemented, indirectly incentivising heat use by offering 20-year bonuses for using residual heat [123]. Many biomass/biogas plants frequently offered residual heat at minimal or no cost to nearby communities, as electricity remuneration constitutes the largest part of the projects' income [107], [124], [125]. This cost advantage motivated citizens close to biogas/biomass plants to connect to a local DH network [74]	*Dutch Climate Agreement* (2019) • *Gradual disconnection of natural gas supply* After earthquake episodes during domestic natural gas extraction [58] and the government climate ambitions, a Climate Agreement was signed in 2019, aiming for the gradual disconnection of all buildings from the natural gas supply by 2050, and 1.5 million houses by 2030 [113] • *Municipal heat planning and role of TECs in the heat transition* (2021) Municipalities received a leading role in the development and execution of local heat decarbonisation plans. They were required to draw up their short- and long-term heat strategy by 2021. TECs can facilitate municipal plans and improve citizen engagement [29], [112]. Initially, many municipalities favoured a top-down approach. However, the crucial role of TECs gained prominence as the challenges of the initial top-down approach by municipalities proved ineffective in garnering people's enthusiasm (INT-26)

Table 5 Other regulatory reforms in Germany and the Netherlands under development which may affect TEC projects

Germany	The Netherlands
New municipal Heat Planning Act and the role of TECs (expected to enter into force in 2024) • A national regulation mandates municipal heat planning because municipalities are not yet obliged to draw up a heat strategy, except in a few federal states [141]. Large municipalities (> 100,000 inhabitants) should submit their plans by 2026 and smaller ones by 2028. To prevent delays, TECs and any DH operator planning new DH networks can submit their proposals before or during the municipal planning phase [139]. Until now, existing municipal plans have not addressed TEC's projects directly (INT-22, INT-24). However, in the final version of the new heat planning Act, energy communities are listed as stakeholders to be considered and involved in drafting the heat plan. Thus, TEC'projects are expected to become more important as a result of the upcoming Act (INT-22). The Heat Planning Act also sets out a 30% share of renewable energy by 2030 and 80% by 2040 to be achieved in DH networks. New DH networks are subject to a 65% share from March 2025 *End of EEG feed-in-tariffs* • The 2014 EEG amendment introduced major cuts in the feed-in tariffs. In 2017, the incentives switched towards an auctioning system [123]. Biogas/biomass plants approved under the old feed-in tariff system could continue to receive support until the end of the 20-year funding period. For many projects, this end will be between 2025 and 2030 [142]. Without feed-in tariffs, projects must substantially adjust their business models as operating costs will increase, affecting the economic feasibility of TEC projects [74], [106] (INT-22)	*Heat Act 2.0 and the role of TECs* (expected to enter into force in 2025) • Announcement that all existing DH systems will be public or semi-public, with a majority of public shares (> 51%). TECs endorsed that all DH systems come into public hands [29], but in the regulatory proposal, TECs were initially not categorised as public entities. Therefore, they claimed to be differentiated from private parties due to their non-profit nature [143], [144]. In July 2023, the objections led to an adaptation of the regulatory draft that is expected to grant TECs the same ownership rights and access to financing options as public companies [138] (INT-02) • The new regulation will emulate the Danish DH tariff system, including cost-based tariffs and transparency rules, aiming to better protect DH consumers from high prices [136] *Municipal ban to stop natural gas supply* (expected to enter into force in 2024) • It will grant municipalities the legal power to ban natural gas supply in buildings to be able to implement local heat plans [62]. This can have a positive impact on the connection rate of all new heat projects, including TEC projects (INT-26)

for the community [97]. The limited commercial incentives brought by the non-profit rule have made the ownership structure in the Danish DH sector largely unchanged since the 1980s [97].

Heavy taxation on oil since 1977, which was increased over the subsequent decades, promoted the development of alternatives to oil and DH systems [126]. This also occurred in Germany, where bioenergy villages emerged in a period of high oil prices [44]. The Danish regulation also included the possibility of enforcing mandatory connections. When participation is compulsory, this means that a unique characteristic of cooperative projects, voluntariness and citizen engagement, is absent [39]. While not always applied, this provision, coupled with the cost-competitiveness and comfort of DH versus alternatives, has led to an impressive average connection rate (~ 80%). This surpasses countries with high DH penetration [85] (INT-27). Germany also has mandatory connection, but municipalities rarely implement it (except for new construction buildings) because it is an unpopular measure [127, 128] (INT-26). The Danish mandatory connection was lifted in 2019 to enhance competition between individual and collective options [129]. This regulatory change has altered the business model for new DH systems or expansions and it may affect tariffs. Støchkel and Sneum [130] calculated a reduction of 70% in the fixed tariff in a scenario with mandatory connection compared to the non-mandatory case.

An obligation to connect limits consumers' freedom of choice, so its implementation must be well justified. In Denmark, every new DH project needs to be assessed from a socio-economic perspective, demonstrating its cost-efficiency and environmental benefits to society compared to alternatives [131]. Only projects demonstrating such conditions are approved by municipalities. Two other key elements of the Danish regulation are the degree of consumer involvement in the decision-making and the provision of stable municipal heat planning, empowering citizen power in companies, and fostering long-term confidence and investments in DH [85]. Unlike Denmark, the emphasis on municipal heat planning and heat decarbonisation of existing building stock has only recently gained political commitment in Germany and the Netherlands. Reducing reliance on natural gas imports has become crucial in the wake of the 2022 energy crisis in the three countries [29, 132] (INT-21, INT-27).

The rapid growth of German TECs between 2009 and 2015 (Fig. 1) can be explained by two important regulatory frameworks: the Cooperatives Act reform of 2006 and, especially, the feed-in tariffs introduced by the Renewable Energy Sources Act (EEG) in 2000. The latter was critical in bringing financial stability to biogas plants for 20 years (Table 4). However, subsequent amendments in the EEG regulation will mean the end of the 20-year subsidy period awarded to many projects, threatening their economic viability (Table 5). There are also examples of Danish CHP plants which suffered economic losses due to sudden reductions in feed-in tariffs for electricity in 2017 [86], [133]. What these facts underscore is that changing regulations can significantly challenge the business case of TECs.

In the Netherlands, the momentum for heat decarbonisation and local heat projects began in 2019 with the signing of the Climate Agreement and the commitment to transforming the heat supply in buildings (Table 5). A significant hurdle for Dutch TECs and the heat transition is the uncertainties concerning the forthcoming Heat Act 2.0 (Table 5), designed to foster DH expansion [134, 135] (INT-06, INT-07, INT-26). The law has been under development since 2020 and is scheduled for 2025; however, it has faced multiple delays, hampering the progress of heat projects [46, 112] (INT-02, INT-05). These delays were partly due to the lack of support from local and regional governments concerning the first regulatory proposal. They sought more influence over DH operations as these involve vital infrastructure, and private firms own most systems now; moreover, several problems were reported, such as cherry-picking only profitable areas and lacking transparency in their tariffs [136]. In 2022, these discussions prompted the central government to transition all existing and future DH infrastructure into (semi)public companies with a majority of public shares [137]. The Dutch government intends to treat TECs as public companies, granting them the same ownership rights and access to favourable loans as other public parties [138] (INT-02). This is an important milestone for TECs, reflecting the government's ambition to give consumers an essential position in the heat transition (INT-02).

By granting TECs a position in regulation, the Netherlands aims to mirror the Danish context and replicate other aspects, such as giving a central role to municipalities (Table 4) and introducing a new DH tariff system (Table 5). In Germany, municipalities are also tasked with implementing heat plans since January 2024 (Table 5). This Act introduces a "forced awareness" of thermal planning. However, the exact role of TEC in the upcoming German municipal heat planning regulation is still unclear. The legislative proposal of July 2023 suggested that only cities with > 45,000 inhabitants must include an assessment of the role of TECs/RECs in actively contributing to implementing municipal heat plans. This limit has been criticised as overly restrictive, given that most TECs operate in smaller areas [139]. The final version of the Heat Municipal Act states that municipalities can or may integrate RECs/TECs into the planning process if their interests are significantly affected by the heat planning or their participation offers significant added value for implementing the heat planning. The German Heat Planning Act is to enter into force at the same time as the Building Energy Act, which requires all to-be installed heating systems in new buildings to be powered by minimum 65% renewable energy (Table 1).

Another significant regulation which may affect TEC projects in the three countries is Article 23 of the Renewable Energy Directive (RED III), approved in 2023. This directive sets more ambitious targets for the decarbonisation of the DH sector compared to its predecessor, RED II. Under RED III, the previously indicative targets are now binding, requiring an annual increase of 0.8% in the renewable energy share by 2026, followed by a more stringent 1.1% annual increase until 2030 [140].

Soft institutions

For effectively executing a DH project, gaining acceptance from the community is crucial but can be challenging. TECs can enhance citizens' participation [22, 29]. Public acceptance and participation in renewable energy projects generally vary across contexts, depending on assessment timing and external- and internal factors [145–147]. Capturing the evolving nature of public attitudes towards TECs in each country is complex and warrants separate, in-depth research. This analysis narrows its scope to four factors influencing the adoption of DH systems and participation in TECs that were highlighted in interviews and literature.

First, the affordability of alternative heating systems plays an essential role in the decision to make the switch [148, 149]. External factors such as policies, energy prices and financial incentives, as illustrated in Hard institutions and Financial infrastructure, influence DH's affordability. When TECs proliferated in Denmark and Germany, DH represented a cheaper and better alternative to traditional oil and coal systems as a result of high energy prices and regulatory incentives. These conditions influenced the operating costs of TEC projects and, thus, the economic attractiveness of DH to potential customers [86, 150]. While this scenario does not always apply under current market conditions, DH prices have seemed less affected by the 2022 energy crisis than those of consumers using natural gas boilers (see Denmark and the Netherlands in Additional file 5). A shift away from Russian gas and the recent high natural gas prices has raised awareness of the heat transition, creating new momentum for TECs [29, 151, 152] (INT-22).

Second, additional factors could drive citizens' decisions to adopt a sustainable heat system, such as environmental concerns, comfort and improving their local economy and autonomy as described by the interviewed TEC projects (Additional file 3) and the literature [7, 22, 82, 145, 149, 153–155]. In the Netherlands, seismic activity from natural gas extraction and the consequent national drive to phase out natural gas raised public

Table 6 Image DH systems in the studied countries

Denmark	Germany	The Netherlands
• The sector profits from a good overall image and trust [116], [163]. DH is a dominant heat technology, and regulation highly protects consumers. End-users see DH as an affordable and reliable system [164], [165] (INT-14). There are hardly any examples of failing TECs translating into high consumer trust in TECs [30], [166] (INT-17). Consumers and developers can be confident that DH is a prudent investment [85], [167]	• Lack of familiarity with DH systems in society (INT-29). There is a mixed image among customers in existing DH systems (mostly municipally owned). Frequent complaints include high prices, lack of transparency and clarity on costs and prices (as there is no tariff regulation), and no free choice of supplier [116], [163]. Before committing, customers want to know the exact costs for DH connections, but these are often unknown [22]	• Lack of familiarity with DH systems in society (INT-26). DH has a mixed image among customers of existing DH systems (owned primarily by private companies and a few local- and regional governments). Frequent complaints include high prices, lack of transparency and clarity of costs and prices and no free choice of supplier [116], [136], [163]. Switching to DH is costly compared to the reference heat system, and costs for connecting are not always known [28], [29], [149], [168] (INT-07)

awareness. Dutch TECs emerged as critical agents in fostering social support and citizen participation [29] (INT-02, INT-09).

Third, the image of DH systems as heat technology or TECs as an alternative model can foster or hamper new customers from joining a project.

Table 6 shows that in Denmark there is a more favourable public perception of and trust in DH (and consequently TECs, given their significant market share, Table 1) than in Germany and the Netherlands. Danish TECs are well-established organisations with a steady history of bringing affordable tariffs and delivering a high-quality heat supply [118] (INT-14) (see also Danish TECs in Additional file 3). Such competitive prices have been achieved through consumer ownership and regulation, in other words, a cost-based tariff system, non-profit and mandatory connection rules, loans at non-financial terms, benchmarking and public disclosure of DH tariffs.[4] Consumer ownership has played a crucial role in getting price regulation to succeed [118, 119]. Although prices can vary significantly among Danish TECs [95], TECs have lower rates compared to municipal and, in particular, private companies [118]. During the interview, the TEC in Lemvig (Additional file 3) proudly mentioned offering the country's third-lowest heating price (INT-11). Next, projects integrating heat and electricity activities have reduced costs by deducting the electricity income from the heat price (INT-10, INT-27). Projects minimise connection costs and offer early sign-up discounts to make the offer more attractive to customers [130] (INT-27). Small TECs have also merged with large companies to offer customers cheaper heat (INT-14).

TECs in the Netherlands and Germany are also committed to keeping tariffs and connection costs as low as possible and rarely intend to make profit [22, 63, 156] (INT-02, INT-22, INT-26, INT-28). Although these benefits can positively impact the commitment of residents, achieving broad participation in new projects is more challenging than in Denmark, with many customers being doubtful, either because they are unfamiliar with the TEC model (INT-02, INT-03, INT-04, INT-22, INT-26, INT-29) and/or DH systems (INT-26, INT-29). Additionally, the image of DH in both countries is mixed, facing frequent consumer complaints (Table 6). However, these complaints primarily reflect those concerning municipal companies (Germany) and privately owned companies (the Netherlands), which constitute most companies in the respective countries (Table 3). We could not find similar complaints in TEC's projects, probably because promoting transparency, good communication and high democratic decision power are central to fostering collective participation [99, 118, 157, 158] (INT-02). The fact that TEC members are often customers also, brings trust and transparency [22, 29]. Yet, if the system TECs promote (i.e., DH) is poorly perceived or unfamiliar, scepticism may arise among residents. In Dutch projects, resistance from citizens preferring alternatives like gas or heat pumps has hindered participatory efforts [159] (INT-06, INT-26).

Fourth, considering that individual heat pump adoption is rising in the three countries [160], residents opting for individual systems challenge the business case of DH projects. If DH is the most cost-effective solution from a socio-economic perspective, it is vital to prevent individual systems from undermining DH implementation [161]. One interviewee indicated that the experience in Denmark is that end-users value DH for its convenience, eliminating the need for individual installations (INT-14). In the Netherlands and Germany, where DH is less widespread than in Denmark, consumers have less experiences with DH for them to draw comparisons. Moreover, the upcoming regulatory changes establishing sustainability standards in to-be-installed heat systems in both countries (Table 1) and the recent energy crisis open opportunities but also pose challenges for TECs and DH projects. Given the time-consuming nature of realising a DH system, heat pumps emerge as a quicker, more autonomous alternative [29] (INT-22). In the Dutch TEC Muiderberg (Additional file 3), the lack of a clear timeline for the DH network made it difficult for the TEC group to discourage residents from investing in heat pumps. This issue also arises when Dutch municipalities have not specified the locations for implementing DH networks in their strategies [162]. In areas lacking DH networks and compulsory connection, it can be very challenging to convince sufficient households to connect to DH (INT-28).

Financial infrastructure

TECs must be capable of raising significant amounts of capital right from the beginning of the project when there are demand uncertainties, and short-term revenues cannot be guaranteed. Depending on the size and scope (e.g., whether the TEC also has generation assets or investments are necessary in buildings), the costs to realise a project can amount to several million euros (see Additional file 3). TECs lack the financial capability to invest substantial sums in projects, primarily due to their relatively small size compared to other DH companies (INT-28). In addition, TEC projects are not always appealing to banks. Projects usually have high transaction costs and low margins, as they are designed to provide heat at low

[4] All DH companies publicly disclose their yearly prices, providing a detailed breakdown of fixed versus variable costs and enabling customers to compare prices across different systems.

costs, generating less substantial financial reserves than traditional solar and wind cooperatives (INT-10, INT-22). Access to initial funding and long-term, low-cost capital is one of the most important limitations for new projects in the Netherlands and Germany [22, 28, 115, 124, 169] (INT-10, INT-22, INT-26, INT-28). However, this challenge has been less prominent in Denmark.

Typical financial sources used are long-term concessional bank loans (often secured by municipal guarantees), equity capital and subsidies (Table 7). Per project and country, these financing resources are employed at different ratios. Denmark offers concessional, long-term loans that are fully backed by municipal guarantees to projects that can prove that implementing DH is the most beneficial option under an established socio-economic methodology (INT-27). Guarantees are essential because they lower financing costs and signify the authorities' confidence and support for the project [86, 124] (INT-27). As no Danish TEC has ever gone bankrupt, these guarantees have never been used in practice [38].

The established experience and stable policy environment for DH in Denmark have resulted in standardised financing procedures and stakeholder confidence [85, 170]. The mandatory connection rule has significantly mitigated investment risks by ensuring a stable and predictable customer base and revenue [70] (INT-13). Nevertheless, since the connection obligation was lifted in Denmark in 2019, new investments have been confronted with uncertain revenue generation, prompting the Danish government to introduce subsidies to projects that need it. The uncertain revenues from not having a mandatory connection are also an issue in the Netherlands and Germany, and they led to higher risks for investors (INT-10, INT-28).

Dutch and German investors perceive TECs as high-risk projects (especially compared to solar and wind projects), translating into difficulty in acquiring debt capital and elevated financing costs [22, 28, 150] (INT-03, INT-10, INT-22, INT-28). In the Netherlands, financing limitations have obstructed the creation of success stories, becoming a self-reinforcement cycle [111]. This problem has also been aggravated because the new Dutch regulation on DH is still under development, creating uncertainties for investors (INT-10). Another problem for new Dutch and German TECs is that acquiring loans depends on municipal guarantees, which are not always available for all projects (Table 7). The following interview passage explains this and other issues for Germany:

> *'In projects of relatively low risk, local cooperative banks in Bavaria have financed projects, leading to a concentration of such cooperatives in the region. However, this pattern hasn't extended to other areas. Municipal guarantees were crucial for other cooperatives, but these depend on whether the municipality is willing and able to give them if it has a deficit. Thus, establishing a state or federal guarantee is being investigated. Since most banks have no experience financing such projects, state guarantees are key to securing funding. Also, with rising interest rates, concessional loans have gone from 1–2% interest to 4–5%, bringing strong implications for the capital costs and profitability.' (INT-22)*

Efforts are also underway in the Netherlands to implement a national guarantee to facilitate external financing and lessen the burden on individual municipalities that face financial difficulties (INT-26). Unlike Denmark, an additional challenge in the Netherlands and Germany is that banks require a substantial equity share when extending loans (Table 7). However, bringing such a level of equity can be challenging for a new TEC with limited financial resources [156].

Public (development) banks have financed Danish TECs in Denmark and some German TECs and it is also anticipated that they will play a significant role in the Netherlands (Table 7). Public institutions usually require lower returns and embrace a longer-term outlook than commercial investors, enabling the funding of projects that might otherwise be deemed too risky or have long payback periods [136, 171, 172] (INT-17).

Subsidies and dedicated cooperative energy funds play an important role in financing the different phases of a project (Additional file 6). Upfront costs linked to the pre-development and development phase (e.g., conducting a feasibility study, legal research, designing the technical system, crafting the business case and gathering community support and external finance) should not be overlooked, particularly in immature TEC markets at the start of the learning curve. In Dutch projects, €8,000–9,000 per house is spent on process-related costs before realisation starts [173]. Only TECs that have received a substantial subsidy have been able to pass the initial phase (INT-26). The potential financial risk of these initial investments in case of an unfavourable outcome is a critical obstacle for many new projects [44, 124].

In the Netherlands, a Grant-to-loan programme is being developed for financing the start phase of TECs [138], which is currently in place for Dutch wind and solar cooperatives but not for TECs [174]. A pilot will be carried out to finance the start phase of 50 Dutch TECs in the coming years [175]. It intends to replace the current model based mainly on subsidies. The revolving fund converts the grant into a repayable loan once the project proceeds, ensuring the fund's long-term capacity to support future ventures. If the project does not

Table 7 Key financing instruments used by TEC projects in the countries studied. List is not exhaustive

	Denmark	Germany	The Netherlands
Concessional loans	• 100% of the investments are usually financed by concessional loans from the Municipal Credit Bank (KommuneKredit), a credit bank owned by all municipalities. It offers cheap loans at 0.4–3% interest rate and for exceptionally long terms (i.e., 30 + years) [70], [180] (INT-13). However, small TECs ("*termonets*", Market structure) have not been able to access these loans and the municipal guarantees because these projects do not fall under the Heat Supply Act [181]. The Act regulates plants with a heat output of more than 25 MW [164], but most *termonets* fall below this threshold • Loans are also sometimes obtained through commercial banks. As heating infrastructure is generally considered a safe, long-term asset (especially in places with connection obligations), commercial interest rates are similar to those of the Municipal Credit bank (INT-13)	• Concessional loans can finance part of the investments; for example, the German Development Bank (KfW) offered loans at a 1–2% interest rate (see TEC St. Peter, Additional file 3). Also, local cooperative banks have financed many TECs (INT-22) • On the national scale, credits are available from the EEWärmeG programme [124], [182] and the Federal Office for Economic Affairs and Export Control (BAFA) [35] • Often, to be eligible for loans, a debt guarantee must be provided (INT-22)	• Concessional loans can finance part of the investments; for example, the TEC of Thermobello acquired a concessional loan from a bank under a municipal guarantee (INT-02) • Commercial banks extend loans if the project can prove sufficient stability in the cash flow [183] (INT-03) or if municipalities provide guarantees (INT-02) * Two public banks aim to provide concessional loans to TECs to finance TECs realisation costs (TNO and Energie Samen Buurtwarmte, 2021) (INT-10)
Government guarantees	• Municipal guarantees secure the concessional loans of the Municipal Credit Bank to projects [85] (INT-11 to 15). The exception is "termonets" (see row Concessional loans) • The municipal guarantees the full debt, but in CHP plants only on the heat-related investments. Electricity generation is considered a commercial activity, and thus, it cannot receive municipal guarantees due to EU state aid rules [184]	• Municipal guarantees sometimes secure concessional loans to TECs, but guarantees are not consistently available to all projects [124] (INT-22) *A federal guarantee is being proposed to help the acquisition of debt capital (INT-22, INT-28)	• The municipality has backed the loan in the TEC Thermobello (INT-02), and a few municipalities have expressed the intention to do so in new projects [30]. In other cases, it is unclear whether such banking will be provided *A national guarantee for DH projects is being investigated [138] (INT-02)
Equity and debt capital	• There is no equity share requirement to acquire debt capital as in Germany and the Netherlands. Equity can be obtained from connection costs in some projects financed by the KommuneKredit (INT-27) • In risk capital provided by banks, the bank may require a part of the infrastructure as a security for its investment	• Banks usually require projects to bring equity for obtaining loans (although there is no minimum requirement as in the Netherlands) [31]. However, it is common to have an equity share of 20–30% [156]. Equity can come from a mix of user connection charges and shareholder capital via subordinated loans [31], [185]	• Dutch banks can only provide loans of up to 70% of the total investment. The rest should come from equity capital (INT-10) • Equity can be gathered through user connection charges, shareholder capital (involving public and private partners) and subsidies—see Dutch TECs in Additional file 3 and KetelhuisWG [183]. Diversifying business areas can generate additional equity capital in projects. This approach is used in the TEC Panningen (Additional file 3)
Subsidies	There are various national, regional, and local subsidies used in projects. See Additional file 6 for an overview of some important subsidies		

* These are instruments which have been proposed or are under development

materialise, there is no repayment obligation. The Dutch TEC Muiderberg received a similar loan from the municipality (Additional file 3). Germany introduced a comparable funding scheme for wind community projects in 2022 but did not include TECs [176](INT-28). Feasibility studies for TECs can be financed with national subsidies [177] as well as with federal state and municipal aid [178, 179].

Physical infrastructure

Implementing a TEC project usually involves changing from an individual to a grid system and switching imported fossil resources to local sources (e.g., biomass, waste heat, and solar thermal) [124]. Bertelsen [186] discusses the challenges of shifting from individual fossil fuel systems with high sunk costs to grid-based home heating. The author highlights that the challenges in the heat transition for countries with a high reliance on large-scale fossil fuel infrastructures and low DH penetration (e.g., the Netherlands and Germany) are much higher than for countries with high DH infrastructure (e.g., Denmark). There are insufficient recent examples of countries realising the transformation from one large-scale infrastructure to another.

Another essential element in a non-fossil fuel DH system is finding an affordable heat source nearby [187]. This can be challenging. Denmark and German TECs have intensively used biomass as sustainable and cost-effective heat alternative (Fig. 2). This trend is also seen in TECs in countries such as Sweden [31] and Austria [107, 188]. In contrast, Dutch TECs overlook biomass as a potential route while at the same time they tackle a unique set of challenges associated with pioneering and less-proven technologies. Below, it is explained that several factors have influenced the observed fuel mix, such as availability, cost-effectiveness, and regulatory incentives for biomass. The local receptiveness and the changing perception of biomass as an alternative source have also played a role in the countries' differences. Biomass has shifted from a relatively unquestioned renewable option to one requiring meticulous evaluation of its environmental and social implications [189–191].

The Danish Heat Supply Act determines that the least costly fuel should be used so as to offer customers the lowest tariffs (INT-27). Due to heavy taxation on fossil fuels since the 1990s, numerous Danish projects switched to biomass, which became a tax-free, short-term and cheap substitute [41, 193]. Although biomass is the most frequently used source at present, many Danish projects still depend on fossil fuels, as the Heat Act historically called for the integration of domestic natural gas in the DH system [65]. However, recent legislation changes have eliminated this requirement (INT-23, INT-27). Today, it is common practice in DH companies to diversify heat sources to utilise the most cost-efficient option under changing market conditions. This ensures stability in heat prices (INT-13, INT-14).

Solid biomass is also used in German TECs, but biogas is the predominant source (Fig. 2). The data examined for the Netherlands in Fig. 2 reflect mostly plans and not implemented sources, contrary to the data shown for Denmark and Germany. While biomass is not a popular source among Dutch TECs (Fig. 2), it is the most frequently used sustainable alternative by other, larger

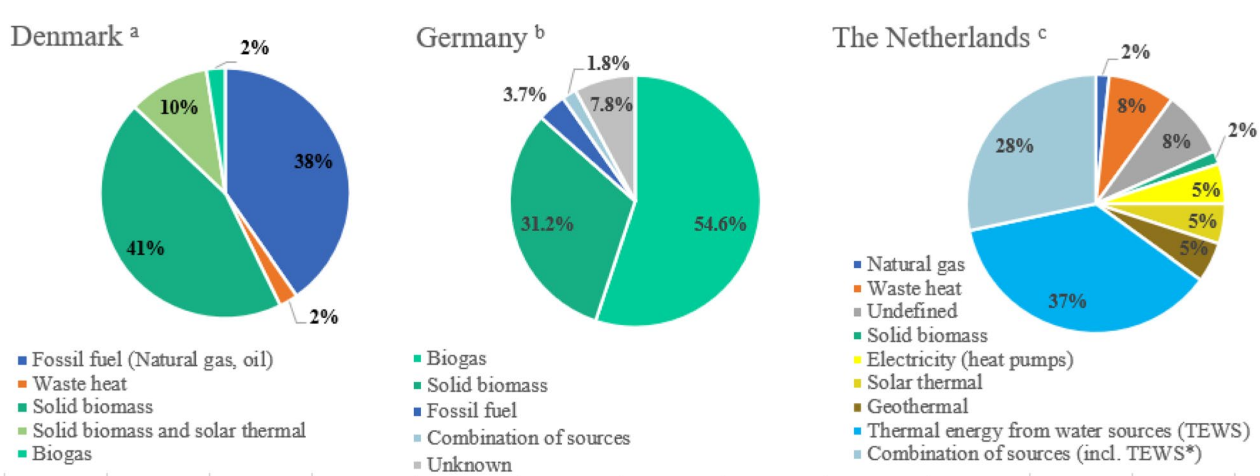


Fig. 2 Main heat sources used in Danish, Dutch and German TECs in 2021–2022. Own figures with data from: [a] [192]; [b] Data from Lars Holstenkamp (co-author) gathered from German Energy Cooperative Database; [c] [45]. Note that the Dutch data concern primarily TECs in the planning stage as only four projects are operational. * The share for the category "combination of sources" for the Netherlands includes 52% of projects that plan to use thermal energy from water sources in combination with other heat systems

Dutch DH companies [96]. Dutch TECs aim for other systems, frequently based on thermal energy from water sources[5] as this source has great potential due to the country's abundant water resources and suitability for small- and large-scale projects [194].

Dutch TECs are experiencing a dual challenge. Thermal energy from water sources is perceived as a new system that has been insufficiently tested among citizens, as the system is not widely implemented in the country [6] (INT-03, INT-18, INT-07). Thus, TECs must gain expertise with these modern technologies while taking on the considerable task of building a new DH infrastructure:

> *'In the Netherlands, we pioneer with innovative sources, but if a source, like biomass, is deemed unsustainable, people are reluctant to proceed with the project. In Denmark, first the infrastructure was established, and later the decarbonisation followed.' (INT-18)*

While biomass offers benefits compared to other renewables, being easily storable and dispatchable [195], the amount that can be used sustainably for heat supply is limited [127] (INT-28). In Denmark and Germany, sustainability concerns regarding biomass-based DH have emerged. Denmark has shifted from oil import dependency to a reliance on biomass imports. While in the 2000s, most biomass and waste were produced locally, the growing demand has resulted in a heavy reliance on biomass imports [70, 129]. In Germany, extensive maize cultivation, commonly used for biogas production, faced criticism within the fuel-versus-food debate [196, 197] (INT-20). Also, the concentration of biogas plants in specific areas has triggered complaints regarding odours, pollutants and noise [150].

TECs in the three countries are challenged to incorporate a growing share of local and non-combustion systems in the future, many based on low-temperature sources [70, 127, 198](INT-29). Lower temperatures increase the possibility of using different heat sources [164]. Some Danish TECs are already planning to move—from high-temperatures (> 80 ℃) to lower temperatures (< 50 ℃) (TEC Viborg in Additional file 3). Solar thermal, waste heat from industry and data centres, shallow ground sources, and heat pumps coupled with seasonal storage are important pillars in future DH systems [26, 198–200]. While these low-temperature sources bring economic and environmental benefits such as reducing pipeline losses and integrating renewables of easy access [94, 201, 202], improving building energy efficiency is the foundation for utilising low-temperature DH [203]. Thus, several constraints at the building level and the electricity grid must be considered in projects (Additional file 7).

Capacity

A lack of capacity, in terms of expertise and workforce, is a shared hurdle among TECs, especially at the initial phase and for small projects (INT-03, INT-06 to 08, INT-13 to 15, INT-21, INT-23). This reflects a common challenge reported earlier in RECs [15, 204, 206]. However, operating a DH infrastructure adds technical intricacies to the relatively straightforward operation of PV panels [207, 208]. Moreover, in many countries, such as the Netherlands and Germany, TECs are relatively young compared to wind and solar community projects, resulting in a shortage of successful examples that can serve as learning experiences for new projects.

TECs typically start with the efforts of a small group or individual citizens, often referred to as the local leaders, champions or entrepreneurs [23, 29, 31, 78, 82, 86, 107]; see also Additional file 3). These dedicated individuals are crucial in initiating, supporting, and executing the project, building trust and engaging a maximum number of citizens [78] (INT-26). These local leaders distribute responsibilities among themselves and key partners in the core team, such as managing the technical assessment, communication and outreach, and financial planning [22, 209] (INT-22).

Expertise is needed in multiple domains, such as technical, financial and legal matters. In addition, strong organisation, leadership and communication skills are needed to involve stakeholders and mobilise investments and committed individuals [107] (INT-23, INT-27). Projects demand new professional qualifications and more time when they become more complex (INT-07, INT-16). However, (small) TECs often have limited capacities, managed by very few paid employees and heavily depending on volunteers [22, 28, 31, 38, 205, 208] (INT-14, INT-23, INT-26, INT-27, see also Additional file 3. Horstink et al. estimated that over two-thirds of community projects, especially those with a not-for-profit orientation, such as TECs, rely heavily on volunteers. While using volunteers can save costs [22](INT-06), sustaining volunteer commitment and willingness to invest a substantial amount of time over an extended period is increasingly challenging [158, 210]. Moreover, many management boards in TECs are run by individuals nearing retirement and it is a challenge to motivate young

[5] There are three water sources that can be used: surface water (e.g., lakes, canals, sea), plants for water treatment, and sewage water. The thermal energy present in water is extracted using heat exchangers. Thermal storage systems are usually implemented to store heat extracted in the summer for use in the winter. As water sources provide low-temperature heat (10–30 ℃), a heat pump is needed to upgrade the water to the required temperature in the buildings [194], [216]

people with sufficient competencies and commitment to join TECs [158, 210] (INT-13, INT-14).

As projects evolve and become more complex, transitioning to a partly or fully paid organisation becomes a strategic necessity [158] (INT-10, INT-18, INT-27). It can enhance the capabilities of TEC's, enabling them to go through complex procedures more effectively and increasing the likelihood of project success [71]. Other approaches that TECs employ to access knowledge and achieve professionalism include establishing partnerships, hiring expertise and utilising training opportunities from intermediary organisations (see Interactions). Additionally, a trend observed in Denmark in recent years involves merging smaller TECs into larger entities to benefit from shared resources, a great pool of human capital and growth in professionalism (INT-13 to 16, INT-27). For example, the TEC in Viborg is a merger of four heating companies (Additional file 3). Larger cooperatives in both Denmark and Germany also provide support and expertise to smaller TECs (INT-13, INT-28).

Interactions

Involving a range of stakeholders from the start of a project can provide the necessary means to sustain and implement community projects successfully [40, 99]. Examples of such means could be financial and non-financial resources (e.g., networking and expertise) and better risk-sharing [98, 158](INT-22, INT-23). In the three countries, local governments play a pivotal role in developing local heat plans and/or DH systems (Table 8). The role of municipalities is often considered critical [46, 124]. Other actors regularly mentioned as important are private companies, banks, building owners, other (neighbouring) TECs, and umbrella organisations.

The type of interaction or collaboration (from occasional to formalised partnerships) and roles may vary among different projects, depending on the local context and needs [29, 30, 210]. For instance, a municipality may support TECs by facilitating their plans, offering resources, networking, and mobilising citizens. In other cases, municipalities may participate more intensively as shareholder/partner, or they can be the project initiators.

The market's maturity in Denmark has also brought established organisations with expertise that provide best practices and readily available information from which Danish TECs profit. One example is the Danish District Heating Association, which acts as an information hub, providing training, industry updates and networking opportunities (INT-11 to 16, INT-17, INT-27). The organisation also represents its stakeholders' interests in lobbying activities [31]. Another good example is the Danish Energy Agency, which offers a technical catalogue with standardised fuel price predictions, cost and heat supply data, and other relevant information to perform reliable and uniform calculations to evaluate DH investments [50].

Table 8 shows that some approaches in the Netherlands and Germany are comparable to those in Denmark. For example, the exchange of knowledge and experiences between TECs is common. Also, intermediary organisations foster collaboration among TECs and provide advocacy, guidance, and support. In Germany, a technology catalogue similar to the Danish one is also proposed [127]. Additionally, giving German and Dutch municipalities legislated responsibilities in heat planning is a process that has just started. However, the countries' relatively limited experience with the heat transition and TEC projects compared to Denmark means that key entities, such as municipalities, investors and consultancies, are still familiarising themselves with these subjects and acquiring expertise:

> *'We were confronted with the fact that no expert in the Netherlands can make a professional business case for our model, only at a very global level, but not at the level of detail that we need to make the right agreements with municipalities and end-users.' (INT-03)*

While the Danish TECs interviewed consider their partnership with the municipality and municipal DH companies positive (INT-11, INT-13, INT-15), barriers have been reported in some projects in the Netherlands and Germany, such as the shortage of expertise, time and financial resources among local governments to deal with TECs and the heat transition [22, 112, 127, 209] (INT-02, INT-03, INT-06 to 08, INT-18). In the Netherlands, for instance, many municipalities are looking for their role; some only want to be facilitators, whereas others want to create their own DH company [30, 136]. Dutch municipalities are experimenting with new forms of cooperation with TECs, and some are unsure how to position these initiates [31, 144]. If municipalities are indecisive about their role, this can delay the progress of TEC projects [29].

Another problem in the cooperation with local governments is that many municipalities lack a clear heat strategy for where DH networks will be realised, prompting citizens to opt for individual solutions such as heat pumps [162]. In other situations, the heat strategy chosen by the municipality does not always correspond with the preferences of TECs. This has happened in a Danish TEC in the past (INT-12) and more recently in Dutch projects [29, 46, 158, 209] (INT-18, INT-26). Such issues are not yet apparent in Germany, probably because most municipalities have not started their local strategies to decarbonise heat in buildings (i.e., low-carbon municipal heat

Table 8 Key stakeholders usually involved in Danish, German and Dutch TEC projects. List is not exhaustive

Actor and roles	Examples from literature and interviews
Local and regional governments • Co-creating: project initiator, shareholder (planning, co-investing, building and operating the system) • Facilitating (heat planning and authorisation, financing, knowledge sharing, mobilising citizens, providing land or facilities, coordinating construction work, providing networking, raising projects' visibility and recognition) • Customer (governmental building connected to the DH network)	*Denmark* For decades, municipalities have been responsible for heat planning and approval of DH projects, sometimes initiating the project [164] (INT-11, INT-15, INT-23, INT-27). They are also part of the board of directors in companies and offer guarantees to TECs to obtain loans [85] (Danish TECs, Additional file 3). Large DH companies, including municipal utilities, play a prominent role in the operation of DH networks, sometimes supporting (smaller) TECs with knowledge sharing (INT-11 to 15) *Germany* In numerous TECs, the municipality has been the initiator [107] (INT-24) (see also ESW projects in Additional file 3). They can also act as shareholders [211]. Municipalities often support TECs with various resources to mobilise citizens [22], [44]. They can also provide public buildings to connect to TEC's network [124]. Municipal utilities play a prominent role in the operation of DH networks, and some support TECs with knowledge sharing [22] (German TECs, Additional file 3) *The Netherlands* The municipality is usually involved, taking various roles from project initiator, project finance to project partner [29], [115], [155], [209] (Dutch TECs, Additional file 3). At the national level, a Knowledge and Learning Programme supports sharing the knowledge gained through the implementation of pilot projects with Dutch municipalities, often involving TECs [114]
Commercial companies (heat producers, engineering companies, banks, energy utilities, project developers, consultants)[b] • Co-creating: project initiator, shareholder (planning, co-investing, building, operating the system) • Provision of heat (heat producers) • Service providers (realisation of DH network and installations, operation and maintenance of the system, financing, project management) • Consultant services and provision of external expertise (technical, financing, legal marketing, sales)	*Denmark* TECs hire private companies to access technical, economic and legal advice—e.g., conducting audits and feasibility studies (INT-12, INT-15, INT-17, INT-27) (see also Danish TECs in Additional file 3). Consulting engineers contribute to project development and proposals. The design and build contract is often tendered to specialised firms [86] (INT-27) *Germany* Farmers operating biogas plants often initiate TEC projects or provide heat to projects [99], [107], [125]. TECs involve professional companies to support them, e.g., planning offices for conducting feasibility studies [44] *The Netherlands* Consultancies, engineering firms, and installers are involved in the planning, design and realisation of projects [115]. Industries or heat producing plants sell their heat to TECs (e.g., Thermobello project, Additional file 3). Interviewees highlighted challenges in finding consulting firms with the right expertise needed for their projects (INT-03, INT-08)
Building owners (private homeowners, housing associations) • Customers • Shareholders in the cooperative	*Denmark* Homeowners buy a share in the TEC project when buying a house connected to the network [86]. According to the Heat Act, citizens can choose the majority of a DH company's board to ensure local ownership and transparency (Hard institutions) *Germany* Engaging citizens and households early helps to achieve higher participation to reach the minimum number of connections required for economic viability [22], [99], [107], [125] (INT-28) *The Netherlands* Projects included high levels of homeowners participation to create awareness and mobilisation [29], [48]. In areas where there is a high share of properties from housing associations, TECs can help them realise their sustainability ambitions, and housing associations can help TECs achieve a high number of connections [29]
Other TECs/RECs • Project initiators • Sharing resources (e.g., personal, administration) • Sharing knowledge: experienced and large TECs can offer know-how to other new and smaller initiatives	*Denmark* Larger or more experienced TECs usually offer support and exchange knowledge with other (smaller) TECs [31](INT-11 to 15). It is common practice that DH companies help each other by combining tenders of infrastructural construction to receive lower prices or by sharing administrative staff (INT-13, INT-16) *Germany* Cooperatives are usually very open to sharing their knowledge with others (INT-22). Citizens from villages with already established TECs were invited to share their experiences with new projects [124] *The Netherlands* Experienced citizen initiatives are usually involved in supporting other TECs with knowledge sharing [115, 212]. In some cases, RECs have initiated a DH cooperative project (see Dutch cases in Additional file 3)

Table 8 (continued)

Actor and roles	Examples from literature and interviews
Umbrella and intermediary organisations • Advocate for favourable policies at local, regional, or national levels • Raise projects' visibility and recognition of RECs/TECs • Information and knowledge sharing (serve as a hub of information, knowledge exchange and create networking opportunities) • Provide training, support and professionalisation (training programmes, educational resources, advice)	*Denmark* The DH association supports its members, and thus TECs (INT-11 to 16, INT-17, INT-27). The Danish Energy Agency offers a technology catalogue to conduct techno-economic evaluations of DH projects [50] *Germany.* The German Cooperatives Association (DGRV) is the central association for cooperatives in various sectors. It provides advisory services, advocacy, cooperation among cooperatives and representation for cooperatives at the national and international level (INT-22). At the Federal level, there are other umbrella organisations helping TECs by providing information, guidance, and opportunities for exchanging experiences [22, 74, 77] *The Netherlands* EnergieSamen is an umbrella organisation supporting RECs and TECs (Henrich and Maas, 2020) (INT-03, INT-06, INT-07). It provides initiatives with information, legal support, and training and it aims to enhance the cooperative sector's professionalism [30]. Other umbrella organisations offering support and knowledge to TECs are the Participatie Coalitie, LSA bewoners, HIER Opgewekt and Natuur en Milieufederaties [31, 46, 209]

strategies), and German TECs are seldom found in cities [35]. However, this situation might change with the new municipal Act (see 'Hard institutions').

Another challenge TECs indicate is the sluggish nature of municipal procedures [44, 115] (INT-03, INT-07, INT-18). However, this issue may also apply to TECs, as they are based on voluntary and part-time efforts (INT-18). For this reason, where finances allow it, projects hire a project manager to oversee expectations and ensure the project works well on both sides (INT-18).

An added complexity is that the accessibility of information for DH design, planning and operation is determined by the existing entities possessing this knowledge. This is different in each country, as Denmark is the only case where DH companies are often citizen-owned:

> *'Danish district heating companies share knowledge easily. You don't need to be afraid that the competitor misuses your information. Our competitors are other technologies, not other companies.' (INT-11)*
> *'Cooperatives in the Netherlands share experiences, but most district heating competencies are concentrated in the private sector, which is not always open to information exchange because this can mean a lost business opportunity.' (INT-10)*
> *'While municipal utility companies engaged and cooperated with TECs, others regarded them as competitors.' (Hartmann and Palm, 2023, p.11)*

Synthesis

Figure 3 summarises the key outcomes of the previous sections, showcasing the facilitating factors or strengths (in bold) and identified barriers (in italics) for Danish, German and Dutch TECs. The overlapping areas show where certain factors apply to two or three countries, illustrating the similarities and differences between the countries.

The growth of TECs in the three countries coincides with the implementation of supportive governmental schemes and several external factors. Regulatory frameworks have fostered the emergence of TECs, such as policies focusing on stimulating DH expansion and strengthening the position of TEC's (Denmark), heat decarbonisation policies (the Netherlands, Denmark), and regulations providing financial incentives to use waste heat in biogas plants (Germany). Other important supporting factors are targeted financing mechanisms and assistance to increase the TECs' capacity and professionalism. In addition to institutional support, external circumstances, such as high oil prices (Denmark and Germany) or seismic events in the Netherlands, have triggered the emergence of communities with environmental inspirations looking for alternative heat systems. Shifting away from Russian gas and the recent high natural gas prices has raised social awareness of the heat transition since 2022, leading to more momentum regarding TECs. Internal factors are also important. Even with a favourable regulatory and policy environment, what remains crucial for the success of TECs is the active participation of the community, along with their ability to take the initiative, organise and collaborate with other stakeholders.

Similarities and differences can also be found in the barriers that TECs encounter across countries. The lack of capacity in small projects is a shared challenge. Additionally, considering the limited amount of local, sustainable biomass, finding cost-effective alternatives is necessary but challenging. The Netherlands and Germany encounter different challenges (green top box in Fig. 3) than Denmark as their starting point differs due to differences in history, in the maturity of the TEC market, and in existing heat infrastructures in place. Denmark

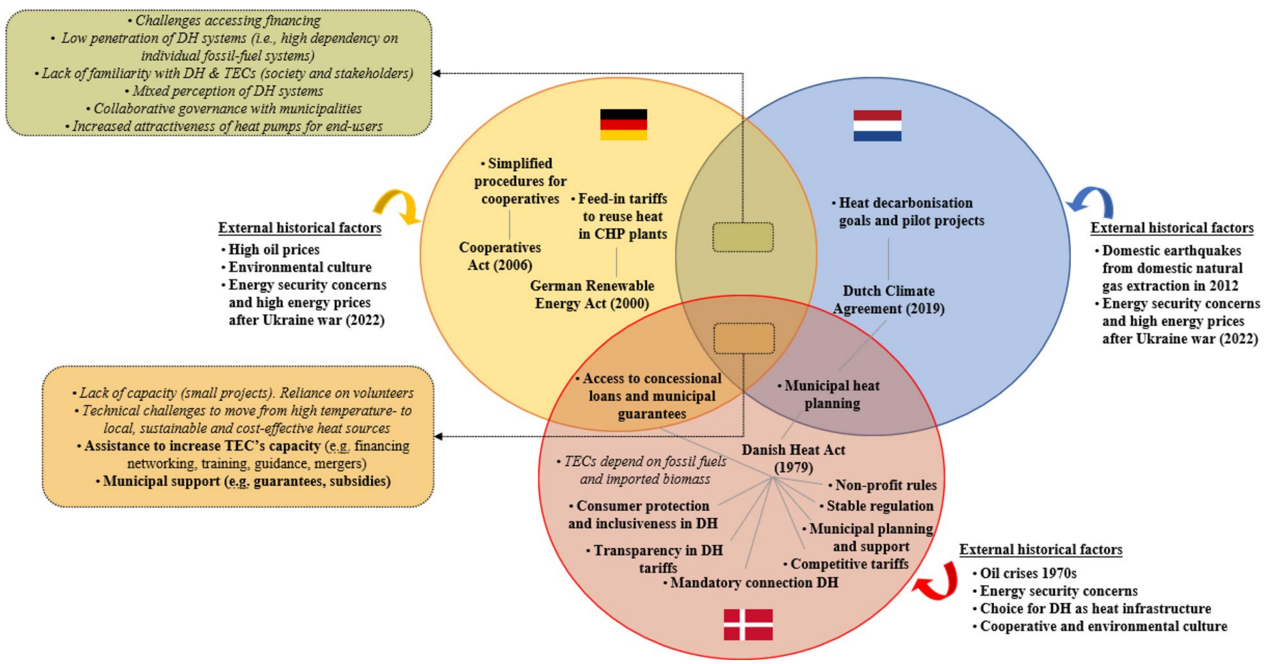


Fig. 3 Synthesis of key identified facilitating factors (bold text) and barriers (italic text) for the emergence and development of TECs' in Denmark, Germany, and the Netherlands

has pursued a move away from fossil fuel-based home heating for decades, benefiting from a stable policy environment, established experiences, and a positive societal perception of DH. These circumstances are not found in Germany and the Netherlands. The TEC route is not mainstreamed yet, especially in the Netherlands, with only a handful of projects in operation, and it has not fully proved its effectiveness. Thus, many of the barriers are associated with a premature socio-technical phase and the inception phase of the heat transition in these countries. TECs encounter financing barriers, a lack of familiarity among residents with the technology, the need to change fossil-based individual technologies with high infrastructure costs, and key policies starting or under development. These factors introduce risks for investors and create barriers to gaining customer trust. The lack of experience is visible at various levels: governments, investors, and society.

Discussion

To our knowledge, this study presents the first comprehensive examination of key factors that facilitate or hinder TEC projects in three different contexts. The study's contribution lies in making a cross-country comparison, expanding on earlier single-country analyses and bringing new insights, assessing seven critical factors to consider in TEC projects while providing a systematic review of recent literature and interview data concerning TECs.

Although we found no studies covering all factors of our analytical framework, some previous studies have explored some of these factors and yielded comparable findings to ours. Relevant cross-country studies include Kranzl et al. [31], which compared TECs across various European countries, highlighting supportive measures, such as policy targets and financial incentives. EnergieSamen [30] compared TECs in the Netherlands and Denmark, emphasising Danish best practices in financing and governance to adopt in the Dutch context, which aligns with the observations of the present work. Szoleczky et al. [86] presented several case studies from Germany, Denmark, Poland and Turkey, noting the importance of community engagement and challenges such as changing regulations and the reliance of TECs/RECs on voluntary work.

Our research illustrates that no single factor was decisive in the emergence and development of TEC projects but rather a mix of contextual factors and diverse forms of institutional support. The study also shows that the context conditions in which TECs operate are continuously changing, bringing new opportunities and/or challenges. Fluctuating energy prices affect DH costs (and, thus, the competitiveness and attractiveness of DH among customers). Another example is the growing adoption rates of individual heat pumps with electricity that are becoming increasingly green [160], which could undermine citizen participation in new DH projects. The landscape of the heat transition and TECs depicted for Germany and the Netherlands might change soon, too, with new and upcoming regulations. Both countries are strengthening their heat decarbonisation strategies and decentralising heat planning to municipalities, as Denmark has done in the past decades. The Dutch government has recognised the potential of TEC initiatives and intends to incorporate additional features of the Danish model. Examples are offering appropriate financing instruments to TECs, giving TECs a position in regulation and enhancing consumer protection in its tariff system. These new regulations might create momentum for new TECs. Additionally, DH networks are expected to grow in the Netherlands and Germany [24, 213], which could enhance the technology's familiarity within society.

While the examined factors of the analytical framework outlined in the Results section are described individually, there is an evident interdependency among them—as earlier highlighted by Mignon and Rüdinger [77], who applied the same analytical framework for RECs. Therefore, the factors studied cannot be addressed in isolation. Our results have shown the following interdependencies:

–Favourable policies ("hard institutions") have increased urgency in society and the willingness to switch heat systems ("soft institutions") in the three countries.
–TECs operating within a supportive institutional framework ("hard institutions"), as in Denmark, still rely on community engagement ("soft institutions"), a certain level of entrepreneurship and organisational capacities of the community groups to thrive ("capacity").
–In Denmark, the combination of stable regulation ("hard institutions") incorporating consumer and investor protection rules with appropriate financing schemes ("financing infrastructure) has been vital in fostering TEC diffusion.
–The absence of a proven record of TEC projects in the Netherlands ("market structure) has led to additional barriers to securing investments ("financial infrastructure") and confidence among potential consumers ("soft institutions").
–The lack of capacity within TEC projects is partly addressed by establishing partnerships with other organisations ("interactions").

Our study provides a starting point for further research to explore the interconnections and the mechanisms behind the factors studied. Future studies may also assess the prioritisation of crucial aspects identified here, determining which challenges or enablers hold greater significance than others in TEC implementation. While the chosen analytical framework enables a holistic grasp of the study topic, it results in a more generalised understanding rather than a detailed examination. Further research might delve into critical aspects identified in this study, including how policies and financing mechanisms could be improved or devising strategies to bolster citizen participation, stakeholder engagement and the broader adoption of DH systems**.**

Although the cross-country comparison of this study can be valuable for countries with TEC initiatives unfolding, it remains uncertain whether all the practices and challenges that we identified in Denmark, Germany, and the Netherlands can be generalised to other contexts with less or more experience with DH and TECs. As most experiences with TEC implementation are concentrated within the Nordic and Western European countries [31], Eastern- and Southern Europe may encounter a distinct set of challenges. Moreover, Danish elements such as the obligation to connect to DH systems, the non-profit rule of DH projects, and the solid and established cooperative culture might make the Danish experience challenging to replicate in other countries. Thus, future research could help understand the applicability of the study's findings to other countries. This can help uncover additional insights into what practices and challenges can be generalised or are context-specific.

Conclusions

Energy communities focusing on collective heat or district heating (DH) systems, also known as thermal energy communities (TECs), have emerged in different countries and at different moments. This study presents the first comprehensive examination of key factors facilitating or hindering TEC projects in three different contexts—Denmark, Germany and the Netherlands, where TECs have emerged at different moments in time.

The study's research question is—What framework conditions influence the emergence and development of TECs in Denmark, Germany, and the Netherlands, and to what extent do these pose a barrier or a strength?'. Rather than a singular factor, the emergence and growth of TECs are the result of a combination of contextual factors and various forms of institutional support. Crucial elements are regulatory frameworks stimulating DH growth and TEC position, heat decarbonisation policies, economic incentives to reuse generated heat in plants, targeted financing mechanisms, and assistance to increase the capacity and professionalism of TECs. In addition to institutional support, external factors such as high oil prices in Denmark and Germany or seismic events in the Netherlands have spurred environmentally inspired communities seeking alternative heat systems. The recent high energy prices and energy-security concerns since the Ukraine war offer new opportunities for TEC projects.

TECs operating within a supportive institutional framework and favourable external conditions depend on additional factors to succeed. Examples are organisational and entrepreneurial abilities to effectively engage with other stakeholders and the community to garner social acceptance and sufficient commitment from community members. Moreover, implementing TECs would be significantly more challenging without the support of the local government, intermediary organisations and private companies.

Danish TECs are the most developed among the three studied countries, profiting from decades of a stable policy environment pursuing a move away from fossil fuel-based home heating, established experiences with DH and TECs, and a positive societal perception of these projects. Conversely, TECs in the Netherlands and Germany encounter distinct challenges because of the early stage of their heat transition, dealing with financial obstacles, underdeveloped policies, unfamiliarity with DH technology and TECs, and the need for expensive infrastructure changes. Shared challenges across regions include capacity limitations in small projects and implementing cost-effective, local, and sustainable heat sources.

The strength of this study lies in its comprehensive examination of key factors that facilitate or hinder TEC projects across three different contexts. It expands on earlier single-country analyses and offers new insights into the differences and similarities between the countries. While the chosen analytical framework provides a holistic understanding of various aspects influencing the development of TECs, it provides a generalised view rather than an in-depth investigation of key aspects. Further research could delve into crucial aspects identified in our work, such as improving current policies and financing mechanisms, enhancing citizen participation, and fostering the adoption of DH systems from TEC projects. Additionally, exploring different settings beyond the countries investigated here could help determine if the findings presented are context-specific or applicable to diverse contexts.

Policy recommendations

In light of the study's findings, policymakers must consider the following measures as essential components of a policy package aiming at effective and efficient implementation and operation of TECs:

- *Establish integrated, flexible and stable policies that support heat decarbonisation systems and TECs, and increase the societal urgency to adopt alternative heat systems.* The Danish example has shown the effectiveness of solid institutional support in terms of robust regulation and financing mechanisms that fostered DH growth, consumer protection and ownership. Financial incentives and fossil fuel bans can also encourage the adoption of renewable heating systems among end-users and reduce dependency on traditional fossil fuel systems. Continuity in support is essential even when the market reaches maturity. Denmark's main policy framework for DH has been sufficiently flexible to evolve and integrate socio-economic and technical dynamics, but it has maintained its core goal: to offering competitive and sustainable DH to end-users. While policy should evolve consistently in the same direction, it must also be sufficiently flexible, responsive and evolving to integrate changing dynamics. TECs initiated in the past, now and in the future face very different circumstances and policy landscapes. Thus, mechanisms should be in place to regularly review and adjust the support provided to ensure it remains aligned with user needs and overall policy objectives.
- *Supporting institutional instruments should also address the TEC's reliance on limited community capacities.* This study has placed particular emphasis on the community aspect of DH. With capacity shortcomings identified in each country studied, it highlights a pervasive key challenge that may also be present in other countries. Thus, it is an area ripe for research and policy action that must be approached thoughtfully. Policymakers, both at the EU and the country level, may prioritise capacity-building programmes to empower TECs, as well as their entrepreneurship, organisational, and professional capabilities. As shown in our research, established community initiatives, intermediaries and other DH companies might be vital for supporting starting and smaller projects. As observed in Denmark, mergers of small TECs into larger companies can also be a plausible strategy to follow in other contexts.
- *Ensure the active participation of TECs in the planning and realisation of local heat plans with municipalities and other stakeholders.* Our research shows that local governments in the three countries play or will soon play a key role in planning and realising the transition to sustainable heat at the local level. Involving TECs in these local plans can deliver numerous co-benefits, such as building social acceptance and trust, leveraging local knowledge, aligning local goals, and enhancing the climate and the local economy. Municipalities are physically close to their communities and well-positioned to understand their needs and challenges. Local governments have access to financial and informational

resources that can support TECs. However, this study illustrates that establishing an effective collaboration and a common vision can be challenging for municipalities with little experience in the heat transition and in dealing with TECs. In this line, it is recommended to support municipal officials and other key stakeholders in enhancing their competencies to engage with TECs and realise local heat strategies.

- *Ensure high DH connection rates in communities where it is the most cost-effective solution from a socio-economic perspective.* Our study describes that residents choosing individual heating systems pose a challenge to the economic viability of DH. Since zoning policies requiring mandatory connection can be unpopular, introducing financial incentives (e.g., subsidies, tax incentives, or reduced connection fees) can make DH systems more economically attractive than individual systems. Also, clear communication about the advantages and cost savings associated with DH can influence residents' choices. Developing tariff structures that make DH pricing competitive and transparent for consumers is essential.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13705-024-00499-4.

Additional file 1: List of interviews

Additional file 2: Interview guide

Additional file 3: Characteristics studied TECs

Additional file 4: Overview key policies over time in Denmark, Germany and the Netherlands

Additional file 5: Influence of policies and energy market dynamics on DH prices

Additional file 6: Overview subsidies

Additional file 7: Technical challenges in low-temperature DH systems

Author contributions

SHM is the lead author and drafted the manuscript. SHM and JM contributed to the conception, design, data acquisition and analysis. DMS and LH also contributed to the data acquisition for Denmark and Germany. All authors contributed to the interpretation of data and the writing and editing of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets supporting the conclusions of this article are included within the article and its supplementary information.

Declarations

Competing interests

The authors declare no competing interests.

Author details

[1]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands. [2]Municipality of The Hague, Department of Urban Development, The Hague, The Netherlands. [3]Energy Sciences, Lund University, Lund, Sweden. [4]Department of Technology, Management and Economics, Technical University, Lyngby, Denmark. [5]Institute of Sustainability Governance, Leuphana University Lueneburg, 21335 Lueneburg, Germany. [6]Institute of Social-Ecological Research and Education, ECOLOG, Lüneburg, Germany. [7]Energy Transition, Netherlands Organisation for Applied Scientific Research, Amsterdam, The Netherlands.

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