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Accelerating transition toward district heating-system decarbonization by policy co-design with key investors: opportunities and challenges

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ABSTRACT

District heating in European, Chinese, and Russian cities is still mainly produced with fossil fuels. Energy-system reconfiguration is essential to achieve full decarbonization, which calls for a greater understanding of how to engage key investors in market transformation and how to formulate effective policy mixes. This article reports on how decarbonization could be accelerated in district-heating systems in Finland with stakeholder orientation especially on key investors consisting of companies focused on district-heating, data-center management, real estate development, and sewage operations. The technological attention is on the excess and ambient heat systems. Drawing from surveys, interviews, and workshops we identified investment barriers and collected policy and strategy proposals to overcome them. The results demonstrate that diversifying and strengthening the policy and strategy mix is needed to overcome barriers related to profitability, political uncertainties, and underdeveloped cooperation and profit-sharing models. Policy co-design with key investors holds potential to improve the effectiveness and acceptability of policies, but with certain limitations as regime actors tend to oppose the types of destabilization needed to achieve full decarbonization of energy systems. Thus, effective policy co-design processes need further development as collaboration is a success factor to achieve climate change-mitigation targets, but simultaneously tensions and conflicts cannot be avoided when accelerating energy-system transformation.

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District heating; energy transition; decarbonization; heat pumps; policy mix; co-design; Finland

Introduction

Climate-change mitigation requires energy-system transformation and the widespread diffusion of low-carbon technologies in only a few decades (IPCC 2022; Levine and Steele 2021). Historically, energy transitions have taken a far longer span to unfold due to long investment cycles of energy infrastructures (Sovacool 2016). Transition toward a decarbonized energy system requires accelerating the diffusion of a mix of low-carbon solutions, which can together replace fossil fuels (Köhler et al. 2019; Lund et al. 2022). The rate of progress toward deep decarbonization has remained slow across sectors (Markard, Geels, and Raven 2020; Rosenbloom and Meadowcroft 2022). This characterization also applies to district heating which provides heat and hot water to buildings and industries across European, Chinese, and Russian cities, and is still mostly produced with fossil fuels (IEA 2022).

To achieve decarbonization of district-heating systems, considerable investments are needed (IEA 2021). Smart Energy and 4th Generation District Heating Systems will integrate various renewable energy and excess heat sources and include capacity for seasonal heat storage, two-way heat connections, and energy-efficiency improvements (Lund et al. 2016, 2018). Especially excess and ambient heat systems have been identified among the main energy-production solutions for decarbonized district-heating systems (Jodeiri et al. 2022; Lund et al. 2022; Pieper et al. 2019). Depending on the case, they include mature technologies such as heat pumps, heat exchangers, and electric boilers with more novel components such as boreholes, storage systems, demand response, and control automation.

In the energy sector, barriers and enabling policies shape investment decisions, as investors consider both potential rewards and associated risks of

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long-term and capital-intensive outlays (Fuss et al. 2008; Masini and Menichetti 2012; Zhang et al. 2019). Some of the previously identified barriers for uptake of the excess and ambient heat systems include poor profitability of the investments, investment risks in relation to political uncertainty, and instability of the industrial excess heat providers (Golub et al. 2018; Lygnerud, Wheatcroft, and Wynn 2019; Lygnerud and Werner 2018). Varying or low heat-source temperatures and the mismatch between the heat supply and end users' heating demand, issues with permitting processes, and lack of actors' competence have also been identified as challenges (Hirvonen, Ur Rehman, and Sirén 2018; Huang et al. 2020; Majuri, Kumpula, and Vuorisalo 2020; Volkova, Mašatin, and Siirde 2018). Furthermore, researchers have pointed to difficulties with cooperation and contracting between district-heating and excess heat-provider companies (Lygnerud 2019; Päivärinne 2017), hurdles in third-party access to the heat-distribution grids (Bürger et al. 2019; Selvakkumaran, Axelsson, and Svensson 2021), and disincentivizing heating and cooling customer-pricing models (Pädam et al. 2019; Paiho et al. 2018).

Simple solutions may not be able to compete against the inertia in socio-technical regimes built over decades (Geels 2018). Setting up policies that tackle the diffusion barriers to low-carbon solutions is important (Koasidis et al. 2020; Markard, Geels, and Raven 2020) and well-conceived policy mixes have been recognized as crucial by Kern, Rogge, and Howlett (2019), Kivimaa and Kern (2016), and Roberts and Geels (2019) in enabling the acceleration of low-carbon energy transitions. The reconfiguration of district-heating systems requires adoption of innovative technologies, reform of markets and legislation, and changes in business models (Fritz, Savin, and Aydemir 2022; Hyysalo et al. 2022; Reda et al. 2021).

The deliberate acceleration of low-carbon energy transitions has become an important research topic (Köhler et al. 2019; Roberts and Geels 2019) with calls for more detailed studies in particular countries and regime-actor contexts. Further research has been suggested by Itten et al. (2021), Kilinc-Ata and Dolmatov (2023), Laakso et al. (2021) and Sillak, Borch, and Sperling (2021) to build better understanding of investor perspectives and the role of regime actors in the governance and dynamics of sustainability transitions.

In the context of district heating-system decarbonization, researchers have not closely examined policy mixes. Such studies are important as distributed production requires a distinction between district-heating companies and heat prosumers, who are proactive consumers that possess assets for local energy generation, conversion, and/or storage (Frölke, Sousa, and Pinson 2022). However, third-party access has been found to be insufficient to support investments toward decarbonized fourth generation district-heating systems (Bürger et al. 2019). Yet an appropriate mix of policies is needed.

The objective of this article is to advance understanding of the acceleration of district-heating decarbonization in two ways. First, we aim to identify acceptable strategies and policies for how to increase excess and ambient heat-system investments which often require collaboration between district-heating companies and third-party heat providers. Second, this article highlights the advantages and disadvantages of regime-actor involvement in policy design. Our research questions are as follows:

- What are the main excess and ambient heat-investment barriers in district-heating systems faced by key investor groups?
- What kind of policies and strategies do key actors propose for overcoming the barriers and to accelerate the diffusion of ambient and excess heat systems? How are these proposals supported by key investor groups?
- How could policy mix co-design with key actors accelerate energy transitions toward decarbonization?

We studied these questions in the empirical context of Finland, where the acceleration of energy-system decarbonization is a legitimate challenge. District heating is the most common heating form in Finland with a 39% share of fossil fuels in 2021 (Statistics Finland 2021). Interestingly, Finland has set a fairly ambitious carbon neutrality target by 2035 in its national Climate Act (Ministry of the Environment 2022). Our participatory research involved key stakeholders to accelerate the diffusion of excess and ambient heat systems in the district-heating grids in Finland. The district-heating and heat-provider companies were the main target groups as the key system investors. We focused on district-heating companies as a key regime-actor group, and on data centers, sewage companies, and building owners as third parties being potential heat prosumers and excess and ambient heat providers.

The article is organized as follows. The next section introduces the empirical and theoretical background. We then describe our research methods and present the results of our study. The final section outlines our conclusions.

Empirical and theoretical background

District heating in Finland

District-heating grids exist in over 200 of Finland's 310 municipalities (Vainio et al. 2015). With over 180 district-heating companies, 47% are owned by cities or municipalities or their companies, 22% by local companies, 22% by other companies, and 16% are cooperatives (Viljainen et al. 2011). The overall district-heating production was 40.8 terawatt hours (TWh) in 2021, out of which 39% was produced with fossil fuels, 47% with renewables being mainly biofuels, and 14% with excess heat from the forest industry, sewage plants, data centers, and other sources (Statistics Finland 2021). District heating generated around 4.4 million tons of carbon-dioxide equivalent (CO_2-eq) emissions, representing approximately 10% of Finland's fuel- and process-based releases in 2020 (Syke 2022).

The diffusion of excess and ambient systems in the district-heating networks was still in a formative phase in 2021, as most of the 90 identified cases were less than five years old (Syke 2021). The adoption of heat pumps has been growing and developing for some time in detached houses (Hyysalo 2021; Lauttamäki and Hyysalo 2019), but recently larger heat pumps have started to compete with district heating, as 500 large apartment buildings installed this technology in 2021 and a significant part of them disconnected from the district-heating grids (Hyysalo and Juntunen 2023; SULPU 2022).

Growth of the heat-pump market has been facilitated by climate policies cascading from directives implemented by the European Union (EU), the Paris climate accord, and the Finnish Climate Change Act (the latter of which sets a carbon-neutrality target for 2035) (Ministry of the Environment 2022). The coal phase-out law, EU emission-trading scheme and national energy subsidies have also been steering district-heating companies to reduce fossil-fuel use. To enhance climate policies, the Finnish government increased the energy content and carbon-dioxide taxes for fossil peat and decreased the electricity tax of the heat pumps connected to district-heating grids. Despite these promising developments, in 2021 the usage of ambient and excess heat was far from its potential in Finland, as only 3 TWh of an estimated 35 TWh of technical excess heat potential was utilized and geothermal heating was still marginal compared to its potential and exceeding by multiple times the country's total heat demand (Kallio 2019; Ministry of Economic Affairs and Employment 2022). To achieve its 2035 carbon-neutrality target, it is crucial for Finland to accelerate the diffusion of heat pumps and other low-carbon energy solutions in heating systems.

Accelerating low-carbon energy investments with policy co-design

Barriers and enabling policies play a crucial role in shaping investment decisions in the energy sector, as energy investments involve long time horizons and significant capital commitments (Fuss et al. 2008; Masini and Menichetti 2012; Zhang et al. 2019). Investors evaluate the profitability and viability of the investments by considering both the potential rewards and the associated risks related to market conditions, technologies, and policy frameworks (Dixit and Pindyck 1994; Masini and Menichetti 2012). Uncertainties include, for example, fluctuating energy prices, technological advancements, regulatory changes, and geopolitical risks (Fuss et al. 2008; Zhang et al. 2019). Barriers include high upfront costs, lack of financing options, inadequate infrastructure, and regulatory hurdles (Fritz, Savin, and Aydemir 2022; Fuss et al. 2008). Companies experience obstacles as deterring or revealed barriers with differences encountered by whether a specific firm is an adopter or non-adopter of advanced technologies (D'Este et al. 2012). According to D'Este et al. (2012), deterring barriers are related to perception of the impediments that prevent companies from committing to innovation and revealed barriers refer to difficulties associated with engagement in novel activities. Deterring effects are particularly important in the case of market barriers, such as demand uncertainty or the presence of established incumbents that prevent new companies from effectively competing.

Policymakers and investors can foster favorable investment conditions by addressing uncertainties and barriers through enabling policies that provide financial incentives, regulatory stability, supportive infrastructure development, research and development funding, and clear long-term vision for the energy sector (Kilinc-Ata and Dolmatov 2023; Masini and Menichetti 2012; Zhang et al. 2019). Policies play a leading role in supporting the emergence and deployment of low-carbon innovations and changing the economic framework conditions (Kivimaa and Kern 2016; Masini and Menichetti 2012). Policy research underscores that effective interventions to accelerate transitions include policy mixes that include both "sticks" and "carrots" and simultaneously foster low-carbon solutions and drive down carbon-intensive arrangements (Kern, Rogge, and Howlett 2019; Rosenbloom and Meadowcroft 2022). Incumbent regime actors can resist, delay, or derail low-carbon transitions, or accelerate them if they reorient their strategies and resources toward innovations (Geels 2014, 2018). Path dependence is a key mechanism that holds socio-technical systems and institutions in their current development trajectories and path-breaking or regime-destabilization policies are intentional attempts to change the existing patterns (Apajalahti and Kungl 2022). As regime actors may stick with old technology beyond its point of competitiveness, policies to activate more resistant actors are also needed (Kivimaa and Kern 2016; Sovacool 2016).

Co-design and co-creation approaches aim to facilitate sustainability transitions by involving key stakeholders to directly work on and interact with the relevant issues (Ceschin and Gaziulusoy 2019; Hyysalo, Perikangas, et al. 2019; Sillak, Borch, and Sperling 2021). Applying co-creation to sustainable heat transitions represents an attempt to solve the lack of progress in decarbonization by facilitating stakeholder participation and interaction with an iterative, reflexive approach (Itten et al. 2021; Sillak, Borch, and Sperling 2021). Co-design can improve the quality and effectiveness of policy decisions by exploring connected issues directly with the implicated actors, including identifying and elaborating socially acceptable solutions (Itten et al. 2021; Lukkarinen et al. 2023; Sillak, Borch, and Sperling 2021). A co-design process by itself does not guarantee that the findings will be taken up in practice in policy or planning procedures, thus involvement of "owners of the system" across jurisdictions is important to establish a multi-level governance process that can facilitate the actions of various decision makers (Itten et al. 2021; Webb et al. 2018). The direct involvement of key actors in structured co-design processes has been found to catalyze a results orientation and identification of concrete solutions across interest conflicts in contrast to hearing procedures and other methods in which participants primarily just express their position (Hyysalo, Perikangas, et al. 2019; Lähteenoja et al. 2022; Lukkarinen et al. 2023).

Materials and methods

Our study was carried out with multiple methods between September 2020 and April 2021 (Figure 1). Building on research on co-design for socio-technical change (Ceschin and Gaziulusoy 2019; Hyysalo et al. 2014; Robertson and Simonsen 2012), we experimented with ways to engage and interact with key stakeholders about energy-system transformations. We created arrangements for joint visioning and organized workshops where district-heating and potential heat-provider companies and experts could identify heat pump-investment barriers and co-create strategies to overcome them.

For selecting research participants, we used stakeholder analysis and mapped organizations and persons affecting sustainable energy investments (Brugha and Varvasovszky 2000), especially focusing on stakeholders from district-heating, data-center, sewage, and large real estate companies that are the main groups in terms of capacity to make excess and ambient heat investments. We also identified and mapped stakeholders from technology and service companies, research institutes, industry associations, municipalities, and government ministries, as they can crucially influence the market and policy development enabling the investments.

We conducted two surveys to collect data regarding ambient and excess heat deployment, investment barriers, and acceleration strategies. The first survey was distributed in September 2020 to over 70 municipalities in the Finnish Carbon Neutral Municipalities network and we received 59 responses but the instrument delivered limited data that was useful for our research due to low expertise level of the respondents. We then administered a subsequent survey in November 2020 and sent it to over 200 experts from district-heating and potential heat-provider companies, researchers, industry associations, and consultancies and received 78 responses. We analyzed the survey results pertaining to the barriers with cluster analysis (Hoen 2002) and strategy proposals with thematic coding (Flick 2009). Barrier analyses were

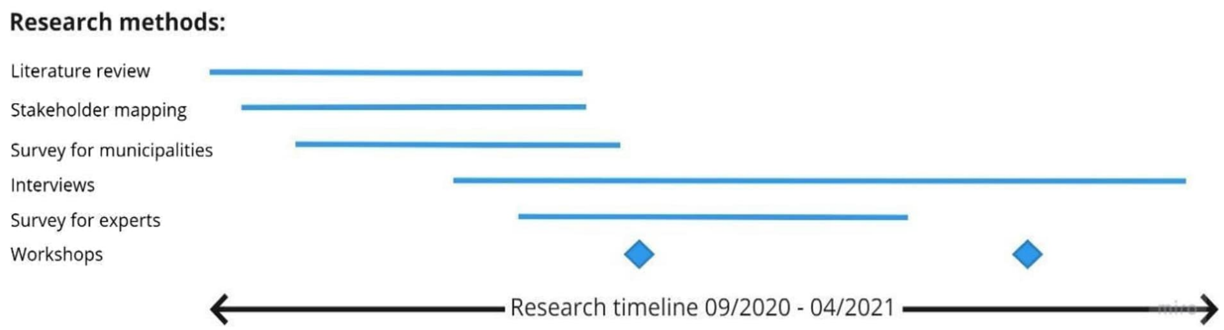

Figure 1. Research methods and timeline.

conducted using the R Statistical language version 4.1.2 (R Core Team 2021). We followed Tumpa et al. (2019) using hierarchical cluster analysis to identify the most important barrier clusters for district-heating and heat-provider companies together and separately. The expert survey-analysis methods are described in more detail in Appendix A. As further outlined below, we evaluated the clusters in light of the expert interviews, workshop feedback, and survey results. Open-ended answers gave us a more complete picture of the respondents' priorities and differences of opinion.

We organized two stakeholder co-design workshops in December 2020 to identify heat pump-investment barriers in the district-heating systems and in March 2021 to identify and score strategies to accelerate the adoption of ambient and excess heat solutions. The material and dialogue mediation for the workshops were built on an online platform allowing the participants to raise their own ideas and to rate or score them and then to exchange opinions both in small groups and among all participants. This setup allowed us to analyze how district-heating and potential heat-provider companies raised and ranked the barriers and strategies. A total of 38 experts joined the first workshop and we created four groups of participants: representatives of large district-heating companies ($n = 14$), representatives of small district-heating companies ($n = 9$), representatives of data-center and sewage companies ($n = 8$), and representatives of large building owners ($n = 7$). Each group was presented with a list of 42 barriers that we compiled from the literature and the interviews as sticky notes in the Padlet tool. The participants were asked to add any unincluded barriers, to vote for the most relevant ones, and to provide written comments. Facilitators then guided the groups in discussions to prioritize approximately the ten most important barriers. In the second workshop two groups were formed: district-heating companies ($n = 11$) and excess and ambient heat-provider companies ($n = 9$). We presented each group with three lists of 8–14 strategies, compiled from surveys and interviews. The participants were again asked to add strategies if the list did not include them yet and to provide written and verbal comments. An acceptability test was made by asking participants in both groups to thumb-up the strategies they supported for implementation and to thumb-down the strategies that they did not endorse.

Based on a methodology developed by Flick (2009), a final dataset was based on semi-structured interviews with 11 experts from research ($n = 1$), district-heating companies ($n = 4$), industry associations ($n = 2$), solution-provider companies ($n = 3$), and a housing company selling excess and ambient heat to a district-heating company ($n = 1$). The interviews were organized as virtual meetings and lasted on average for one hour. The interviews were conducted to deepen insights about barriers, policies, and strategies.

Analysis of the barriers and strategies was based on recordings and transcriptions of the expert interviews and group discussions in the workshops, field notes, and written comments from the surveys and workshops. We categorized and numbered the barriers prioritized in the survey responses following PESTEL (political, economic, socio-cultural, technical, environmental, and legal) dimensions as they provided a general idea about the macro-environmental conditions (Yüksel 2012). We then cross-checked how the barriers were addressed by the proposed strategies (see tables presented in the results section).

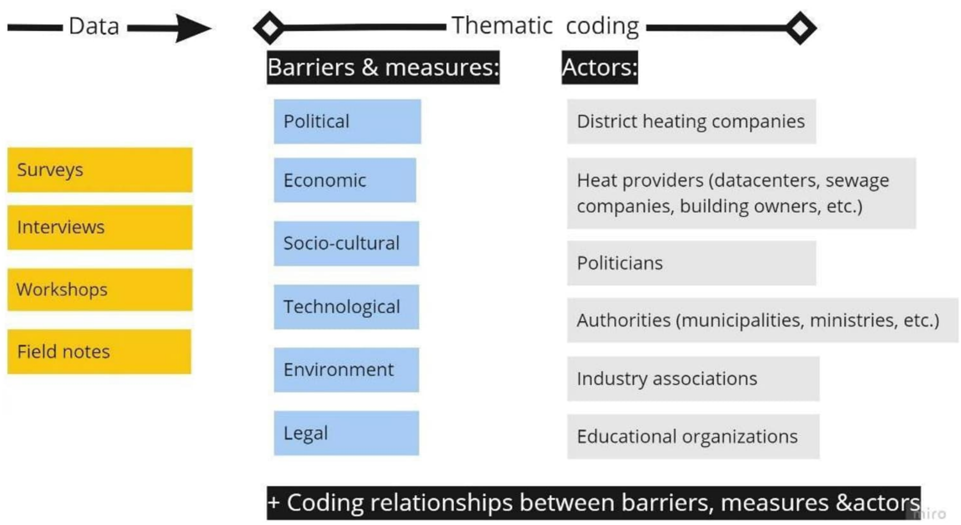

Figure 2. The categories used in thematic coding of barriers, strategies, and actors.

In an analysis with thematic coding using the qualitative research tool NVivo (Bazeley and Jackson 2013), we triangulated the data looking for patterns across all sources to overcome the limitations of a single method (Flick 2009) (Figure 2). We collected the data in Finnish, made the analysis by translating materials, and drafted the results in English as presented in this article.

Results

Diffusion and investment barriers

The stakeholders identified 36 barriers to heat-pump investments. In the survey, 16 barriers were pointed to as the most significant ones to be solved by the key investor groups of district-heating companies and heat providers including data-center, sewage, and real estate companies (Figure 3).

We analyzed how the barriers converged and diverged between the key investor groups. Overall, the interviews and survey results revealed that there were many tensions between the district-heating and heat-provider companies as well as a lack of understanding of one another's reasoning behind the barriers.

The cluster analysis of the barriers identified in the survey found five clusters (Figure 4). The description of the procedure used in the cluster analysis and the tables of summary statistics are provided in Appendix A.

The most significant barrier cluster over all respondents was related to the poor profitability of the investments (see cluster 1 in Figure 4, and ECO 1, 2, 3, and 4 in Figure 3). The risks related to the stability of the excess heat provider (ECO 4 in Figure 3) were considered to be a significant barrier among the district-heating companies, especially as it related to industrial excess heat providers in case they went bankrupt, moved the production unit to another country or location, or limited the production process due to market fluctuations. By contrast, the heat providers expressed concern that the excess and ambient heat-purchase prices were too low (ECO 3 in Figure 3). Several interviewees complained that the district heating-tariff structures and price models in their current form, with a large portion of a water-flow fee being fixed for the year, were not incentivizing building owners to adopt ambient heat, excess heat recovery, or demand-response solutions for their own use or for sales to the district-heating grids.

> Excess heat investments will not be profitable as long as the district-heating company in a monopoly position takes a very big slice of the district-heating bill as a fixed cost. Large building owners are

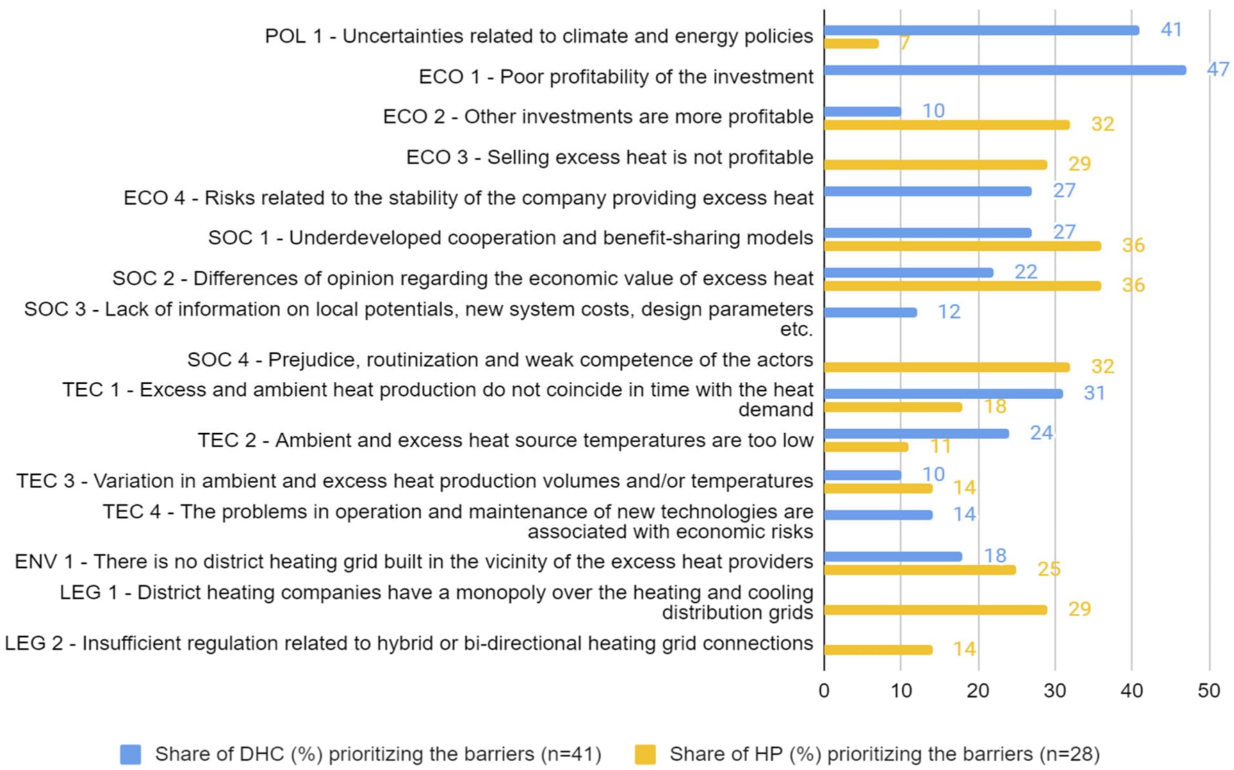

Figure 3. Answers by district-heating companies (DHC) and heat providers (HP) to the survey question: "Select the top 3 barriers which are important to solve to increase excess and ambient heat use in the district-heating systems?" *Note*: Barriers are categorized in the figure as political = POL, economic = ECO, socio-cultural = SOC, technological = TEC, environmental = ENV, and legal = LEG.

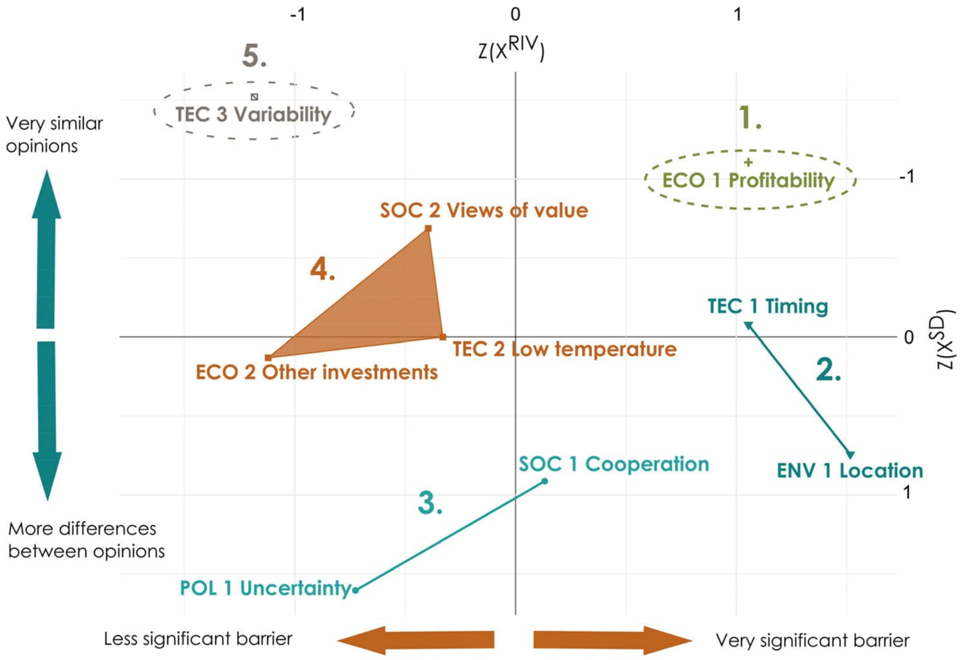

Figure 4. Five barrier clusters in the significance-opinions matrix. *Note*: Barriers evaluated by all survey respondents divided into clusters 1–5. Cluster 1 was considered to be very significant among all respondents. Clusters 2, 3, and 4 comprise barriers that were considered significant but with more differences in opinions across all respondents. Cluster 5 received the most consistent evaluations from all respondents, but with the lowest mean.

> economically in a situation where it is necessary to either get rid of the district-heating connection completely or do nothing (Interviewee from the real estate company).

The policy uncertainty (POL 1 in Figure 3) referring to changes in tax levels, subsidies, and technical regulations between four-year governments was perceived to be more detrimental by the district-heating companies (see cluster 3 in Figure 4).

> The investment risk is too high when the operating and payback times of energy technologies are longer than election periods (Interviewee from district-heating company).

> The investment environment is unstable due to the volatility of political decision-making (Interviewee from district-heating company).

The investors in general considered the excess and ambient heat systems to be technically and economically challenging due to reasons such as low and varying source-temperature levels and mismatch between ambient and excess heat availability and heat demand (see TEC 1, 2, and 3 in Figure 3). Regarding these technical challenges, mainly representatives of the district-heating companies considered that cost and space-efficient seasonal thermal storage was not yet available and that load management would become more challenging in heat distribution with more production units. Generating heat from low-temperature ambient heat sources to high temperature-district heating would require heat pumps that consumed a lot of electricity and would lead to excessive increases in heat-production prices. A further complaint was that the heat exchangers in the buildings do not allow the temperature of the district-heating grids to be lowered. The problems in operation and maintenance of new technologies (TEC 4) were associated with the possibility of rising electricity-market prices and the lack of proper warranties to manage investment risks.

According to the survey data, within the district heating-company group the firms that had already made investments or were currently in the process of doing so had selected technical barriers (see TEC 1, 2, and 4 in Figure 3) more often as their top three barriers than those that had not made any investments. The companies that had not made investments yet tended to select cooperation challenges (SOC 1, 2) more often as their top three. In the interviews, especially the representatives from companies that had not yet made investments emphasized multiple reasons why the heat-pump systems were immature, risky, and not yet lucrative, while representatives from firms that had already made investments considered them technically mature and profitable. Underdeveloped cooperation and profit-sharing models (SOC 1), and the differences in opinion regarding the economic value of the excess heat (SOC 2) were identified as difficulties by both groups but were considered as more significant barriers by heat providers (see cluster 3 in Figure 4).

Different business and investment timespans, which are longer for district-heating companies than in industries providing excess heat, were mentioned as reasons that cause profitability and cooperation challenges (see ECO 1, 2, 3, and 4 and SOC 1 and 2 in Figure 3) and thus business mismatches.

> There is no WIN-WIN situation between district-heating companies and excess heat providers. In practice, the challenge is to share the benefits between at least two, often three, actors. If all parties are not winning, nothing will happen (Interviewee from a district-heating company).

In general, respondents identified a lack of knowledge and competence as barriers (see SOC 3 and 4 in Figure 3). Several experts pointed out that poor competence and outdated data used by the consultants and the technical system designers (SOC 3) had discouraged many excess and ambient heat investments for the wrong reasons. Interviewees from district-heating companies furthermore complained that politicians, civil servants, and "environmentalists" had poor understanding of the energy systems, the energy business, and the positive societal value of district-heating systems. The heat providers also identified a lack of knowledge, routinization, and negative attitudes (SOC 4) as reasons behind the inaction and resistance of conservative district-heating companies.

Both groups recognized the missing district-heating grids next to the potential industrial excess heat providers (see ENV 1 in Figure 3) as a barrier. Municipalities were commonly criticized for slow and outdated land use-planning practices.

> Sewage-treatment plants are deliberately zoned as far as possible from the residential areas. Therefore, only self-use of excess heat may be profitable, but not the district-heating production because the construction of the missing pipeline is so expensive (Interviewee from a sewage company).

The heat providers addressed a lack of third-party access and insufficient regulation related to hybrid or bi-directional heating grid connections to the heat-distribution grids as significant barriers (see LEG 1 and 2 in Figure 3). District-heating companies were criticized for having a monopoly over the heating and cooling distribution grids (LEG 1). Some also criticized that the current organizational structure in district-heating companies did not fit the distributed energy business.

Proposed strategies for accelerating the diffusion of excess and ambient heat systems

Altogether 33 strategies were proposed by the experts in interviews, workshops, and surveys to tackle prioritized investment barriers. We divided them into technical (Table 1), economic (Table 2), regulatory (Table 3), and cooperation and business-model (Table 4) categories. The actors responsible for implementing the proposed strategies included politicians, authorities, industry organizations, educational institutions, district-heating companies, and heat providers. These actors are delineated in Tables 1–4, where they are listed in parentheses.

Technical strategies

Overall, district-heating and heat-provider companies mostly supported the technical strategies (Table 1). Technical strategies included increased usage of heat storage, smart control automation, and temperature-control technologies to enable distributed production.

They proposed building a new type of low-temperature heat-distribution grid in new construction areas and the usage of the cooling grids for low-temperature heat exchange during the heating season as strategies for the more cost-efficient use of heat pumps. Both groups favored construction of thermal storage capacity to control the temporal variability of

Table 1. Proposed technical strategies with acceptability test results.

Technical strategies	Targeted barriers	Would you support this strategy? DHC Yes	No	HP Yes	No
Construction of heat storage to control the temporal variability of certain ambient and excess heat temperatures (DHC, HP)	TEC 1, TEC 3	9		9	
Enabling distributed production by guidelines and optimizing DH systems with intelligent control and metering automation (DHC)	TEC 1, TEC 3, SOC 1	7		5	
Targeting R&D to reduce technology and product costs (authorities)	ECO 1, ECO 2	3		8	
Focusing R&D to heat-storage technologies, in particular on less space-consuming and cheaper seasonal storage solutions (authorities)	TEC 1, TEC 3, ECO 1	7		4	1
Focusing R&D on, for example. geothermal energy-drilling technologies and high-temperature heat-pump solutions (authorities)	TEC 2	8	3	5	
Establishing low-temperature heat-distribution grids in new construction areas (authorities)	TEC 2, ECO 1, ECO 3	5	2	7	
Decreasing by 1 °C degree per year the flow temperature of the district-heating grids and fixing and optimizing customers' heat exchangers and systems as challenges arise (DHC)	TEC 2, ECO 1, SOC 1	5		4	1

Note: DHC: district-heating companies; HP: heating providers.

Table 2. Proposed economic strategies and policies with acceptability test results.

Subsidies, tax reliefs, and other policies	Targeted barriers	Would you support this strategy? DHC: Yes	DHC: No	HP: Yes	HP: No
Politically binding long-term roadmap covering energy taxes and subsidies (politicians)	POL 1	10		9	
Implementing the electricity-tax reduction for the heat pumps producing district heating (politicians)	ECO 1, ECO 2, TEC 2	9		8	1
Introducing new subsidy or a "scrapping premium" for upgrading the heat exchangers of buildings that would allow for lowering the district heating-grid temperature (politicians)	ECO 1, ECO 3, TEC 2	9		7	1
Perseverance with technology pilot and demonstration subsidies and R&D support until prices have stabilized to lower levels (politicians)	ECO 1, ECO 2	7		7	
Active application of and increased use of EU grants and other funding (DHC, HP, authorities, industry and educational organizations)	ECO 1, ECO 2, ECO 3, TEC 2	7		5	
Reduction of counterparty/investment risk related to the instability of excess heat providers by a state guarantee or an insurance arrangement for 10–20 years (politicians)	ECO 4, SOC 4, TEC 3	9		4	2
Improving the design, accessibility, and suitability of existing investment grants and subsidies (authorities)	ECO 1, ECO 3, SOC 1, TEC 4	6	1	2	
Long-term subsidies for electricity generation (politicians)	ECO 1, TEC 2	7		2	2
Requesting smaller dividends from municipal energy companies to enable investments (authorities)	ECO 1, SOC 1	1	1	2	
New investment grants (politicians)	ECO 1, TEC 4	4	3	1	2

Note: DHC: district-heating companies; HP: heating providers.

the air, water, solar, and certain industrial source-heat temperatures as well as better balancing of the heat demand with production. Representatives of several district-heating companies reported ongoing investments in new heat-storage capacity, but they simultaneously emphasized a need for further research and development efforts, especially for the deployment of seasonal heat storage with smaller space requirements and higher thermal capacity. Furthermore, lowering the temperature and increasing the smart control of the district-heating grids were considered crucial.

> The reduction of the temperature level in the district-heating grid is a key to the large-scale use of excess heat, as it puts all profitability calculations in a new light (Workshop participant from a heat-provider company).

Economic policies and strategies

Most of the companies favored economic policy instruments such as subsidies and tax relief as strategies to improve the economic profitability of the investments (Table 2), as affordability and economic reliability were fundamental needs for district-heating and heat-provider companies. Economic strategies furthermore consisted of the improved use and development of the existing subsidies, rather than introducing completely new investment grants.

The companies especially supported the formation of a long-term policy roadmap of energy taxes and subsidies that would be agreed to by all political parties so it would extend beyond the four-year parliamentary periods. Both groups emphasized the importance of the deduction of the electricity tax for heat pumps. Several district heating-company representatives stated the implementation of this policy was groundbreaking for the feasibility of the heat-pump investments.

> The electricity-tax reduction is crucial for the large projects. We cannot make investment decisions of millions of euros until this tax change has been implemented (Workshop participant from a district-heating company).

Both groups favored a new "scrapping premium" subsidy for upgrading the heat exchangers in buildings. Renewal of the heat exchangers was considered to be an elemental improvement for lowering the temperature of the existing district-heating grids.

Both groups considered investment subsidies and R&D funding provided by the Finnish government and EU as important for improving profitability. The continuation of these allocations was seen as necessary until excess and ambient heat system and heat-storage costs decreased to a more competitive level. Furthermore, both groups supported a guarantee or insurance arrangement provided by the state-owned fund to mitigate the stability risk of the excess heat providers.

Regulatory strategies

Regulatory strategies (Table 3) consisted of coercive strategies and improving land use-planning practices, permitting procedures, and building codes. Several regulatory strategies created divergence of opinions among participants. Representatives of district-heating companies, and especially those from data-center and sewage companies, emphasized that land-use planners in municipalities should always seek to locate excess heat providers next to the district-heating

Table 3. The proposed regulatory strategies with acceptability test results.

		Would you support this strategy?			
		DHC		HP	
Regulatory strategies	Targeted barriers	Yes	No	Yes	No
Zoning new buildings and industries along existing DH grids according to circular economy principles (authorities)	SOC 1, SOC 4, ENV 1	11		6	1
Streamlining and speeding up municipal permitting and zoning processes to minimize indirect costs (authorities)	ECO 1, ECO 2	1		7	
Renewal of the DH grid connection standards for the buildings enabling more profitable utilization of property-specific excess heat sources (politicians/industry organizations)	ECO 2, ECO 3, SOC 1, TEC 2	4	1	2	1
Introducing new building codes and guidelines for changing the heat exchangers and re-adjusting control equipment in the buildings for lowering the temperature of the DH grids (authorities)	ECO 2, TEC 2	4	4		1
Opening the DH markets for competition by, for example, separating production and heat distribution grid to different companies (politicians)	SOC 1, SOC 4, LEG 1, LEG 2		5	3	2
Including unsustainable biomass to EU emission trading scheme (politicians)	ECO 2	1	9	3	1
Forcing DH companies to receive excess and ambient heating to their grids with set tariffs (politicians)	ECO 3, SOC 1, SOC 2, SOC 4, LEG 1, LEG 2		10	3	1
Forcing data centers and industries to deliver their excess heat to the DH grids with regulation or "penalty" taxes (politicians)	ECO 1, SOC 1, SOC 2, SOC 4, LEG 4		9	3	5

Note: DHC: district-heating companies; HP: heating providers.

grids. According to the interviewees, it was still common for land-use planners to establish zones for industrial facilities, data centers, and sewage plants far from residential areas.

> New buildings and industries producing excess heat should be zoned along the district-heating grids, otherwise profitability declines too much, or building the grid connection is not even possible (Interviewee from a district-heating company).

Amending building codes to speed up renewal of the heat exchangers in buildings resulted in divided views among the respondents from district-heating companies. Some of them considered it as an effective measure while others feared the Ministry of the Environment as an authority would not be able to set the requirements properly and therefore favored the industry's own standards as a measure to promote renewal of the heat exchangers. "Stick" regulations such as mandatory obligations or payments were mostly disliked by both groups.

> Coercions and sanctions are ill-suited to democracy and a market economy (Workshop participant from a heat-provider company).

> Forcing never brings good results, a carrot is better than a stick (Workshop participant from a district-heating company).

The heat-provider companies called for policy interventions that would disrupt the monopoly of the district-heating companies over the grids and pricing structures. Policy proposals made by heat providers to open third-party access to district-heating grids or improve pricing models to incentivize excess and ambient heat use, were disfavored by representatives of the district-heating companies. Furthermore, two (out of five) heat providers did not support separating the production and heat-distribution grid between different companies. Some heat providers considered that it was not the correct measure to improve the economic profitability of the ambient and heat investments. They expressed concern that such regulatory change could take a very long time to implement and "in the hands of unprofessional decisionmakers" lead to implementation of a model that would only increase heating costs instead of promoting low-carbon investments.

Cooperation and business model-development strategies

Overall, district-heating and heat-provider companies supported most strategies to develop cooperation models, and voluntary business-model development enabling better collaboration (Table 4). Both groups especially favored strategies enhancing bilateral cooperation through model contracts and good revenue-sharing examples. Furthermore, new service models and the creation of new facilitated foras for increased interaction and partnership formation were somewhat supported. An hourly pricing model was not seriously considered as a proper strategy to promote investments.

The potential of a co-designed policy mix to accelerate district heating-system transition toward decarbonization

The large number of intertwined and remaining barriers indicate the current policy mix is insufficient to orient the transition of the heating systems toward decarbonization in accordance with the timeline of the Finnish carbon-neutrality target of 2035. Several actors, and especially the companies which had not yet made excess or ambient heat investments, emphasized that all of the listed barriers were

Table 4. The proposed cooperation and business model-development strategies with acceptability test results.

		Would you support this strategy?			
		DHC:		HP:	
Contracts, cooperation, and business models	Targeted barriers	Yes	No	Yes	No
Creating model contracts between DH and excess HP companies (industry organizations)	SOC 1, SOC 4, TEC 4	8		9	
Gathering good examples of cooperation, contracts and revenue-sharing models between DH and HP companies (industry/educational organizations)	ECO 3, SOC 1, SOC 2, SOC 4	8		2	
Developing end-customer pricing and contract models that encourage the self-use of excess heat or sales to the DH grids (DHC)	ECO 3, SOC 1, SOC 2, TEC 2	4	1	6	
Creating a two-way DH model through discussions with customers (DHC)	SOC 1, LEG 2	3		5	
Changing DH business models so that decentralized and centralized solutions are combined to one customer service (DHC)	ECO 3, SOC 1	1		5	
Building bridges and working together: combining industries' climate roadmaps and pushing actors for cooperation (authorities)	SOC 1, SOC 3, SOC 4	3		2	
Initiating cooperation between DH companies and excess heat providers by facilitating first meetings (authorities/industry organizations)	SOC 1, SOC 4	3	2	4	
Transferring heat pricing and billing models to hourly pricing to promote energy efficiency and demand response (DHC/politicians)	TEC 1, TEC 3	2	1	3	1

Note: DHC: district-heating companies; HP: heating providers.

simultaneously relevant to some extent, creating a lot of investment uncertainty. We found that deterring barriers among non-adopters of new technologies were more significant and versatile than revealed barriers identified by the companies that had already made excess and ambient heat investments. The technology adopters emphasized the need for capacity-building among non-adaptors and stressed the leading role of companies with abundant R&D resources to pave the way for companies suffering from financial and personnel scarcity. For accelerating investments, deterring barriers should not be overlooked but solved, as the emission-reduction targets require investments from a majority of actors who have not yet adopted low-carbon heating solutions. Thus, the policies and strategies should be implemented simultaneously for reducing investment uncertainty and tackling the prevailing mix of barriers. The analysis indicated the proposed mix of strategies and policies hold potential to overcome comprehensively the prioritized barriers and to accelerate the diffusion of ambient and excess heat systems in the Finnish district-heating grids. Poor economic profitability, market constraints, lack of cooperation, and technology immaturities were identified as significant barriers, which could be tackled by a mix of economic policy instruments, new legislation, renewed business and cooperation models, and capacity-building efforts.

However, the actors proposed multiple changes mainly to “others” rather than to their own organization or their own investor group. Representatives of the district-heating companies mostly suggested changes for the authorities and politicians and heat-provider companies and highlighted initiatives for district-heating companies, politicians, and authorities. Furthermore, our analysis of the interviews and workshop discussions revealed that district-heating, data-center, sewage, and real estate companies were not aware of each other's policy preferences. In addition, the industry organizations were not aware of their member companies' needs in relation to the development of cooperation models or the need for increased subsidies. This determination attests to the potential that co-design can have in advancing decarbonization in this domain as it brings actors and their barriers and preferences in direct contact and opens them for mutual elaboration.

Discussion and conclusions

The investment barriers that we identified in Finland were similar to several barriers that other researchers such as Fritz, Savin, and Aydemir (2022) and Jodeiri et al. (2022) have highlighted for other Nordic and European countries. The wide range of remaining barriers concretize the hurdles and complexity in increasing the pace of diffusion of low-carbon solutions in the district-heating systems. As effective policy mixes are vital in transformative processes (Kern, Rogge, and Howlett 2019; Rosenbloom and Meadowcroft 2022), strengthening policies with improved industrial, national, and international collaborations are needed to accelerate market and technology development (Lund et al. 2022; Malhotra and Schmidt 2020; Sovacool, Geels, and Iskandarova 2022). Our results support the findings that several strategies are required simultaneously to accelerate the energy transition toward decarbonization in district heating as well. The policies should simultaneously include R&D support for novel technologies and business models, initiatives to improve the competitiveness of clean energy technologies and to mobilize private spending, and enhance capacity-building and partnerships among governments, research, and industries (Kilinc-Ata and Dolmatov 2023; Madurai Elavarasan et al. 2022).

As the use of excess heat is required to succeed with the full decarbonization of the district-heating systems (Lund et al. 2022; Ravelli 2022; Yuan et al. 2021), improving related economic incentives and cooperation models is needed. According to our study, allowing excess heat providers and other third parties to access the district-heating grids is essential in combination with economic incentives, cooperation, and capacity-building efforts. None of these strategies alone could tackle the identified investment barriers sufficiently, but when combined the accelerated diffusion of excess and ambient heat systems is likely to take place. Our study found that key investors on both the supply and demand sides strongly favored economic incentives such as subsidies and tax reductions. While the nature of preferred subsidies could partly be seen as incumbent actors' attempts to shift the financial burden and risks to government, they nonetheless represent "carrots" toward adoption of low-carbon solutions. Following the policy preferences of the investors, the politicians would need to be willing to implement a public budget that enabled strategies to assure real impact on emission reductions. Recognizing that the Finnish government has legitimate interests in the preferred policy mix and cost-distribution, the policies investors preferred should be viewed as elaborated interest statements in the policy-setting process.

Development of the policy mix should consider the challenges related to the coupling of the district-heating and electricity sectors. After we completed the data collection for this study in 2020–2021, the prices of emission-allowance units (EUA) and electricity prices approximately quadrupled by 2022–2023 (Ember 2023; Statistics Finland 2023). The main reasons were the emission-trading scheme (ETS) improvements by the EU and the energy-market impacts caused by the Russian war in Ukraine. Higher ETS prices do incentivize companies to invest in cleaner technologies (Fuss et al. 2008) but the high electricity price led to a decrease of excess heat use in Finland in 2022 as ambient and excess heat systems largely include electric heat pumps (Energiateollisuus 2023). In this study, representatives of the district-heating companies referred to the risk of rising electricity prices as one of their investment concerns. As deep decarbonization requires wide electrification of fossil fuel-based applications in the energy sector, ensuring the security of electricity-centered systems, handling the price volatility (Madurai Elavarasan et al. 2022), and redesigning the market model (Keppler, Quemin, and Saguan 2022) are relevant aspects to consider in the formulation of the policy mix.

The combination of policies and strategies should focus on achieving the country's overall climate goals by reducing investment uncertainties in the energy sector. According to our study, in the case of new excess and ambient heat systems, the deterring barriers among non-adapters were more significant and widespread than revealed barriers among system adopters. This is a different finding compared to D'Este et al. (2012) who found that revealed barriers can be more significant in firms engaged in innovation activities than the deterring barriers. Our finding may point to the risk-aversion behavior common among investors in the energy sector, the tendency by companies to avoid system complexity that increases in the decarbonization of the district-heating systems, or to the path-dependence and technology lock-in among the incumbent actors. To mitigate the uncertainties in a changing investment landscape, investors would benefit from the creation of a politically binding long-term roadmap covering energy taxes and subsidies as a means of increasing longer-term predictability of investment conditions. This proposition was one of the most widely supported strategies in our research among the key investors. At the same time, capacity-building processes should enhance knowledge transfer from the early adaptors toward the potential majority adopters to encourage implementation of the investments under inevitably uncertain conditions.

This study lends support to the potential that stakeholder involvement holds in the transformation of existing socio-technical regimes (Geels 2018; Sillak, Borch, and Sperling 2021; Webb et al. 2018). The barrier perceptions and policy preferences of key actors can help in the design of a better targeted and more acceptable policy mix. Acceleration of energy transitions toward decarbonization would greatly benefit from higher coherence between policymakers and influential technology adopters, shared visions on needed systemic changes, and collaborative efforts (Hyysalo, Marttila, et al. 2019; Lund et al. 2022; Roberts and Geels 2019). Our research reveals that the regime actors in Finland were not aware of each other's barriers or policy preferences and did not have a shared transition agenda with related collaboration, which points to lack of policy co-design arenas with joint problem-solving and low-carbon solution-diffusion focuses. Our findings encourage better understanding of the needs of key regime actors and their investment preconditions to low-carbon solutions in the effective design of a policy mix to accelerate sustainable heating transitions (Itten et al. 2021). Co-design interventions can help to identify and formulate the core problems to tackle relevant issues, to co-create solutions, and to facilitate collaboration between key regime actors from different sectors and disciplines (Hyysalo, Perikangas, et al. 2019). Co-design processes and the coordination of actions between policymakers, intermediary actors, new entrants, and different regime actors is crucial to accelerate low-carbon energy transitions (Hyysalo, Perikangas, et al. 2019; Itten et al. 2021; Webb et al. 2018).

To achieve full-system decarbonization, coercive and regime destabilization strategies leading to path break-out have been considered necessary (Apajalahti and Kungl 2022; Rosenbloom and Meadowcroft 2022). Indeed, the policy proposals made by the representatives of heat-provider companies to open third-party access to district-heating grids or to improve pricing models to incentivize excess and ambient heat use were not favorably embraced by their counterparts from the district-heating companies. Defense of the status quo among incumbent actors seemed to prevail and the need for transformational changes in the own-actor groups was not recognized (see also Apajalahti and Kungl 2022; Heiskanen et al. 2018). Instead, the actors proposed multiple policy changes and actions mainly to be implemented by others. As it is evident that the policy mix for better utilization of excess and ambient heat reserves in Finnish district heating will also have to include less preferred coercive strategies to bring transformational changes toward decarbonized district-heating systems (Malhotra and Schmidt 2020; Reda et al. 2021; Yuan et al. 2021), policy co-design processes could include conflict-mediation techniques (Peltonen and Sairinen 2010).

We conclude that policy co-design with key investors has the potential to accelerate energy transitions toward decarbonization when the focus is on removing investment barriers and the influence of regime actors is not allowed to water down the meeting of climate goals or impose policies that favor incumbent companies. This approach has the potential to open new possibilities for effectively managing the policy processes as well as related tensions in democratic societies involving the interplay of politics, industrial relations, technology development, and market dynamics. Policy co-design processes that simultaneously mediate conflicts and produce effective outcomes should be developed and studied further by researchers and policymakers. Eventually, efforts to pair destabilization strategies with subsides incentivizing incumbent-regime companies to adopt low-carbon solutions appear necessary to achieve decarbonization of Finland's district-heating systems.

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Data availability statement

Research data such as survey reports, ambient and excess heat case and company lists, and summary of the workshops (in Finnish) are publicly available at the Finnish Environmental Institute Syke website (https://www.hiilineutraalisuomi.fi/fi-FI/Ilmastotyo/Energia/Hukka_ja_ymparistolammon_kasvun_esteet_j(59173)).

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Appendix A

Expert survey-analysis methods and results

The expert-survey respondents were asked to rate barriers (see lists below) on a five-point Likert-like scale from “Not significant at all” to “Very significant” (see Table A.1) and then to choose exactly three main barriers and to suggest related strategies.

Barriers in the expert survey all respondents:

- There is no district-heating network in the vicinity of the heat source
- Weak profitability of excess heat sales/poor return on investment
- Heat production and heat demand do not meet in time
- Lack of cooperation and benefit-sharing models with excess heat providers/district-heating companies
- The temperature of the ambient or excess heat is too low
- Differences of opinion on the economic value of excess heat
- Uncertainties related to climate policy and the energy markets under disruption
- Other investments are more profitable (e.g., biomass and waste incineration)
- Variability in the production volume and temperature of the heat source

Table A.1. Strategies of significance and their numeric conversion*.

Survey-item scale	Numeric value
Not significant at all	1
Not very significant	2
Somewhat significant	3
Fairly significant	4
Very significant	5

*Shows the conversion of Likert-based categories to numeric values used in the following cluster analysis and calculation of means and standard deviations for the evaluations of the barriers.

Table A.2. Significance of barriers across all respondents.

Barriers	Likert value mean	Likert value std. dev	Mean scaled	Std. dev scaled
There is no district-heating network in the vicinity of the heat source	3.72	1.27	1.52	0.99
Weak profitability of excess heat sales/poor return on investment	3.63	1.08	1.06	−1.47
Heat production and heat demand do not meet in time	3.63	1.18	1.06	−0.10
Lack of cooperation and benefit-sharing models with excess heat providers/ district-heating companies	3.44	1.29	0.13	1.21
The temperature of the ambient or excess heat is too low	3.35	1.19	−0.33	0.00
Differences of opinion on the economic value of excess heat	3.33	1.12	−0.40	−0.91
Uncertainties related to climate policy and the energy markets under disruption	3.27	1.36	−0.73	2.13
Other investments are more profitable (e.g., biomass and waste incineration)	3.19	1.20	−1.12	0.17
Variability in the production volume and temperature of the heat source	3.17	1.03	−1.19	−2.02
Average	3.41	1.19		

Table A.3. Significance of barrier classes across all respondents.

Class	Class average mean	Class average standard deviation	# of barriers in class
Political	3.27	1.36	1
Economic	3.41	1.14	2
Social	3.39	1.20	2
Technological	3.38	1.14	3
Environmental	3.72	1.27	1
Legal	–	–	0

Barriers in the expert survey for district-heating companies:

- There is no district-heating network in the vicinity of the heat source
- Heat production and heat demand do not meet in time
- Poor return on investment
- Risks related to the permanence of excess heat supply
- Uncertainties related to climate policy and the energy markets under disruption
- The temperature of the ambient or excess heat is too low
- Variability in the production volume and temperature of the heat source
- Differences of opinion on the economic value of excess heat
- There are financial risks associated with the operation and maintenance of new technologies
- Lack of cooperation and benefit-sharing models with excess heat providers/district-heating companies
- Other investments are more profitable
- The sizing of the existing district-heating network
- Lack of information (e.g., on heat sources, system costs)
- Load management in heat distribution becomes more difficult with the increase in heat sources

Barriers in the expert survey for excess heat providers:

- Undeveloped cooperation and benefit-sharing models with district-heating companies
- Challenges in the culture of the actors (e.g., prejudice, inability to overcome established routines, or poor skills)
- There is no district-heating network in the vicinity of the heat source
- The temperature of the ambient or excess heat is too low
- District-heating companies have a monopoly on the heating network
- Other investments are more profitable
- Weak profitability of excess heat sales
- Insufficient regulation related to hybrid or bi-directional heating-network connections
- Insufficient support from society
- Heat production and heat demand do not meet in time
- Uncertainties related to climate policy and the energy markets under disruption
- Variability in the production volume and temperature of the heat source
- Differences of opinion on the economic value of excess heat
- Zoning challenges (e.g., location, schedules)

This allowed us to study how the respondents and adopter groups prioritized the barriers (see Tables A.2–7).

Selected barriers are represented by X_i, where i = (1,2,3…m) and m is the number of barriers. The importance is measured using relative importance value (RIV), that is the mean of the evaluations of the respondents (X_i^RIV) and standard deviation (SD) to measure the differences in opinions (XiSD).

For each barrier, a relative significance value (X^{RIV}) was determined by calculating the mean of the answers given by the respondents to each barrier after being converted to numeric values (see Tables A.2–7). Both relative significance and standard deviation variables are standardized using equations by Kaufman and Rousseeuw (1990) to get Z(XRIV) and Z(XSD). The cluster distances were calculated using Euclidean distances with group-average linkage. Silhouette methods and visual inspection of the dendrograms were used to find the optimal number of clusters.

In Figure 4 in the article, the barrier clusters show the standardized relative significance and its standard deviation values on the Y-axis and X-axis respectively. The higher the Z(XRIV), the more significant the barrier was rated, and the lower the Z(XSD) value the lower the differences in opinions. The use of standard deviations (Z(XSD)) allowed us to consider heterogeneity in the opinions instead of ranking the barriers only according to standardized means (Z(XRIV)).

Table A.4. Significance of barriers for district-heat companies.

Variable	Likert value mean	Likert value std. dev	Mean scaled	Std. dev scaled
There is no district-heating network in the vicinity of the heat source	3.85	1.13	1.22	0.44
Heat production and heat demand do not meet in time	3.83	1.04	1.18	−0.46
Poor return on investment	3.73	0.87	0.94	−2.12
Risks related to the permanence of excess heat supply	3.69	1.24	0.84	1.53
Uncertainties related to climate policy and the energy markets under disruption	3.65	1.25	0.75	1.59
The temperature of the ambient or excess heat is too low	3.54	1.15	0.51	0.62
Variability in the production volume and temperature of the heat source	3.42	0.92	0.22	−1.63
Differences of opinion on the economic value of excess heat	3.29	1.05	−0.06	−0.33
There are financial risks associated with the operation and maintenance of new technologies	3.27	0.92	−0.11	−1.65
Lack of cooperation and benefit-sharing models with excess heat providers/ district-heating companies	3.17	1.14	−0.35	0.50
Other investments are more profitable	3.08	1.20	−0.54	1.13
The sizing of the existing district heating network	2.77	1.06	−1.26	−0.28
Lack of information (e.g., on heat sources, system costs)	2.69	1.21	−1.45	1.19
Load management in heat distribution becomes more difficult with the increase in heat sources	2.50	1.03	−1.88	−0.52
Average	3.32	1.08		

Table A.5. Significance of barrier classes across district-heat companies.

Class	Class average mean	Class average standard deviation	# Of barriers in class
Political	3.65	1.25	1
Economic	3.50	1.10	3
Social	3.05	1.13	3
Technological	3.52	1.01	4
Environmental	3.85	1.13	1
Legal	–	–	0

Table A.6. Significance of barriers for heat providers.

Barriers	Likert value mean	Likert value std. dev	Mean scaled	Std. dev scaled
Undeveloped cooperation and benefit-sharing models with district-heating companies	3.93	1.41	1.77	1.21
Challenges in the culture of the actors (e.g., prejudice, rutting or poor skills)	3.70	1.30	1.20	0.00
There is no district-heating network in the vicinity of the heat source	3.48	1.48	0.64	1.88
The temperature of the ambient or excess heat is too low	3.00	1.21	−0.57	−0.90
District-heating companies have a monopoly on the heating network	3.52	1.40	0.74	1.05
Other investments are more profitable	3.37	1.21	0.36	−0.85
Weak profitability of excess heat sales	3.44	1.37	0.55	0.75
Insufficient regulation related to hybrid or bi-directional heating network connections	3.15	1.43	−0.20	1.43
Insufficient support from society	2.81	1.21	−1.04	−0.88
Heat production and heat demand do not meet in time	3.26	1.35	0.08	0.54
Uncertainties related to climate policy and the energy markets under disruption	2.59	1.31	−1.60	0.14
Variability in the production volume and temperature of the heat source	2.74	1.10	−1.23	−2.08
Differences of opinion on the economic value of excess heat	3.41	1.25	0.45	−0.49
Zoning challenges (e.g., location, schedules)	2.78	1.12	−1.14	−1.81
Average	3.23	1.30		

Table A.7. Significance of barrier classes across heat providers.

Class	Class average mean	Class average standard deviation	# Of barriers in class
Political	2.59	1.31	1
Economic	3.41	1.29	2
Social	3.67	1.33	2
Technological	3.00	1.22	3
Environmental	3.48	1.48	1
Legal	3.33	1.42	2