



Transition pathway for the city toward low-emission district heating system with heat auctions promoting third-party network access

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Abstract

Here a plausible transition management model to accelerate the decarbonization of urban district heating systems is presented. Many cities and energy utilities have struggled in identifying sustainable, socially acceptable, and cost-efficient solutions to replace fossil fuels and unsustainable biofuels. A model was developed based on a case study made for the City of Helsinki in Finland to phase out coal and to reach carbon neutrality without additional bioenergy capacity by 2035. Methods included energy system modeling, environmental and economic assessment, and transition pathway co-creation. The main technical solutions included heat pump systems, demand response, energy storage, and strengthening electricity distribution networks. Achieving cost-efficient and socially acceptable local energy transition requires decentralizing heating solutions. The city can accelerate investments and promote third-party network access through heat auctions, open energy map data, and fast-track permits. Urban transitions need to be iteratively managed based on energy system modeling to secure sufficient heat supply, cost-efficiency, and rapid decarbonization simultaneously. Adoption of a new operational, business and market models is challenging but necessary. More research and development are needed on heat auctions and local energy transition management models, which enable coordinated investments by multiple actors to reach zero-emission district heating systems.

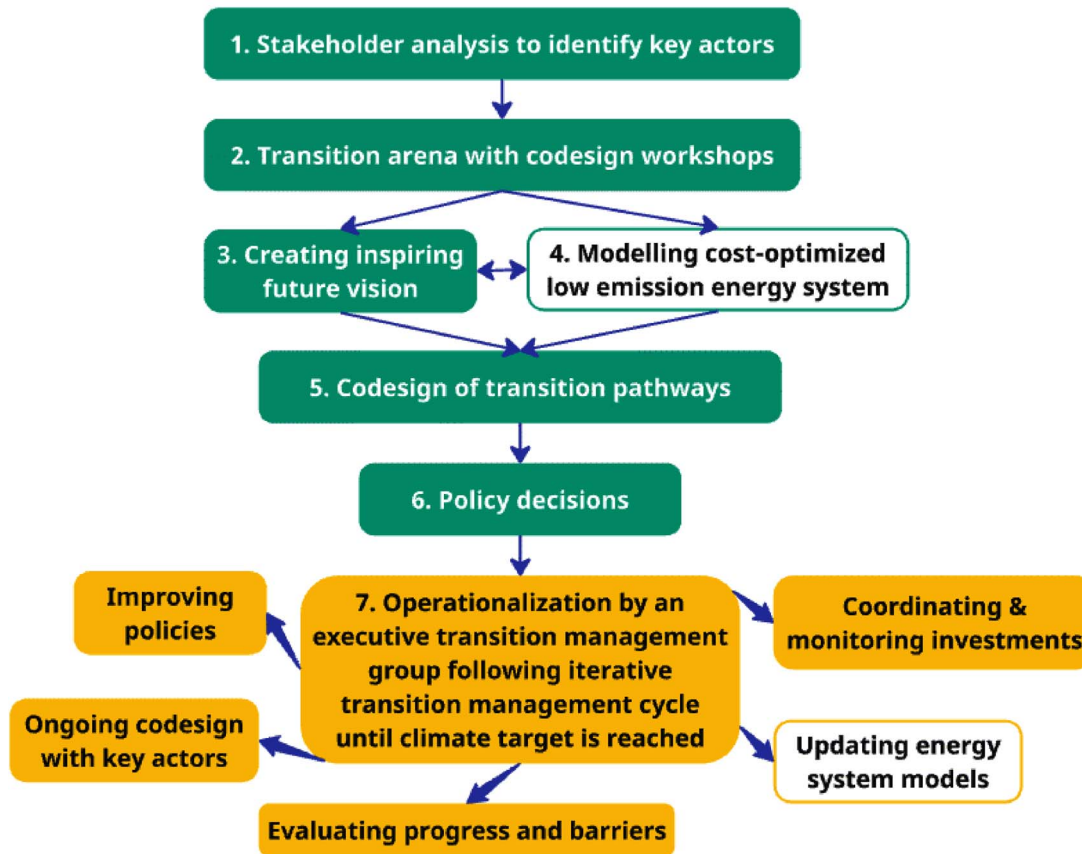
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Graphical Abstract

Transition management model for accelerating energy transitions toward low emission district heating systems



To meet climate change mitigation goals, a rapid phase-out of fossil fuels is essential. However, progress has been slow, with ~90% of district heating still reliant on fossil fuels. Accelerating the zero-emission transition requires major investments in energy efficiency, excess heat recovery, renewable energy, and storage. This study proposes a transition management model and outlines technologies, policies, and actions to help cities achieve zero-emission district heating systems. Key recommendations include: establishing a transition committee; implementing clean heating auctions; creating an open energy map; and introducing fast-track permits.

Key words: district heating; energy transition; transition pathway; energy system modeling; decarbonization; city policies

Introduction

Decarbonizing district heating in parallel with overall energy systems is a prerequisite for achieving the targets set in the Paris Climate Agreement to limit the global temperature rise to 1.5–2°C and corresponding net-zero emission targets, but the progress has remained slow [1–5]. Reaching zero emissions in the energy systems might be required within just the next few decades, especially if anticipated reductions in deforestation and pasture land use do not materialize as current deforestation trends suggest [6–9]. The lack of advancement in emission reductions applies particularly to district heating systems located mostly in Chinese, Russian, and European cities, as ~90% of the heat production was still based on fossil fuels in 2021 [10]. Significant efforts are needed from multiple actors to rapidly improve the energy efficiency of the district heating networks and buildings, and to switch from fossil fuels to low-emission heat sources

[10–12]. The development of Smart Energy and fourth Generation District Heating systems is necessary with considerable and synchronized investments in renewable energy, excess heat sources, heat storages, two-way heat connections, and energy efficiency improvements [4, 13–15].

Several cities and companies have been facing challenges in identifying and integrating sustainable, socially acceptable, and cost-efficient solutions to replace fossil fuels in the district heating systems [16–19]. Cities often lack capacity and governmental support to develop local energy concepts and governance models for the adoption of sustainable solutions [20–22]. The decarbonization strategies of the district heating systems have been largely relying on a bioenergy as a substitute of fossil fuels, but the ecologic and economic sustainability of biofuels has been questioned [23–27]. Global bioenergy use should be capped at a sustainable level of ~100 billion terajoules (TJ), up from the

current 70 billion TJ (~19 500 TWh), with a shift toward more sustainable sources, such as waste streams and short-rotation woody crops, that do not require additional land use [6, 28, 29].

A wealth of knowledge already exists on the technological alternatives to decarbonize district heating systems so that the biomass incineration remains within sustainable limits [11, 13]. However, several market and other socio-economic barriers hinder the overall energy transition [5, 30, 31]. Integrating low-emission technologies in urban settings while safeguarding energy security requires sophisticated decision-making tools, new energy management strategies, and business models [32]. Distributed production requires changes to the structure and operation of district heating markets [33–35].

The current district heating markets are heterogeneous and do not often incentivize distributed production, demand response and energy efficiency improvements in buildings [18, 36, 37]. Excess heat from data centers, electrolysers, buildings, and industrial processes are in general provided by third parties bound to district heating systems with reduced autonomy [33, 34, 38, 39]. District heating companies can limit their network access as they control the heat production and distribution [40, 41]. The question of how the third-party heat prosumers can access district heating systems has remained unresolved [34, 40].

Decarbonization of district heating systems requires long-term public and private investments, coordinated initiatives, and specific regulations and financing strategies due to their capital-intensive nature [10, 11, 42]. Local policies have been found to be crucial to accelerate low-emission energy expansions with long investment cycles [42, 43]. Transformational changes invariably occur in a manner that is specific to their context, influenced by various factors, such as local urban infrastructure, environmental conditions, and different actors with their corresponding strategies [44]. Location-specific knowledge is needed to identify effective transition management approaches in different urban settings [45–48].

More research is needed to understand how to manage regional transitions toward zero-emission district heating systems in different regulatory, technical, and societal settings [15, 39, 49]. Accelerating transitions in cities requires tailoring location-specific enablers, support measures and policies [16, 20, 21]. Several cities in Canada, China, and Europe incorporated actions to reduce emissions from district heating systems as part of their climate plans, though the importance of national-level steering has been highlighted [50–52]. Integrating and coordinating national and local energy planning is crucial, as zero-emission solutions are mostly implemented at the local level [21]. In growing cities, the rising energy demand has often counteracted the efforts to reduce emissions, whereas in shrinking municipalities, the combination of population decline, improved building energy efficiency, milder winters, and competition from building-based heat pumps have posed challenges for updating polluting heat production systems [53]. Today, most of the European countries do not support cities well in preparing strategic spatial plans for decarbonizing heating and cooling, and thus EU's updated Energy Efficiency Directive includes an obligation to do so [50, 54, 55].

Our research question is: *How can a City accelerate the decarbonization of the local district heating system while striving for cost-efficiency, security of supply, and social acceptance?*

In this paper, we introduce the Urban Transition Management Model for Zero-Emission District Heating Systems, developed based on the results and lessons learned from our case analysis of the City of Helsinki. The capital of Finland was

searching for sustainable heating solutions through the Helsinki Energy Challenge in 2021, an innovation contest aimed at articulating demand for system-level transformation to decarbonize its district heating system. [56, 57]. We co-created a transition pathway for the city based on analysis made with energy system, and environmental and economic impact assessment modeling. Our proposed management model aims at making a theoretical contribution to the Transition Management Framework [58, 59]. There is a lack of studies proposing transition management models applied to local district heating transitions, which require accelerated efforts by the city in coordination with other key actors.

This article is organized as follows. “Energy transition management” section introduces literature. The methods and data are described in “Case study setting materials and methods” section. Results are presented in “Results” section. Discussion follows in “Discussion” section and “Conclusions” section provides conclusions.

Energy transition management

The Transition Management Framework is a governance theory for sustainability transitions, developed to empower transformative social innovations and to provide practical guidance for accelerating transitions [58–60]. It aims to gradually destabilize unsustainable regimes while fostering short-term innovations and actions linked to desired societal transitions [31, 58].

The Transition Management approach is adaptable to different contexts, recognizing each process's unique actors, problems, and solutions [58, 60]. It involves establishing transition arenas, developing visions, creating pathways using back-casting techniques, experimentation, and ongoing monitoring and evaluation [58, 61]. Anticipatory action, societal experimentation, and policy changes are elemental to achieve transformative shifts in socio-technical systems [58, 62–65].

Effective governance, strategic energy planning, and robust policies are crucial for managing and guiding complex changes in energy systems [43, 66]. Given the unpredictability of complex systems, transition management is circular, iterative, and error-friendly method, allowing actions to adapt as situations change and knowledge evolves [31, 58, 60]. Using designed tools, actors can outline transition pathways that detail progressive actions, such as policies, strategies, and investments, to achieve time-bound targets and desired visions [59, 60, 65, 67]. Energy system models and tools are essential to plan future energy transition pathways, understand related costs, and estimate the required investment scales to secure sufficient energy supply [2, 68, 69].

In urban settings, executing energy system transformations is complex because of the multitude of stakeholders engaged and the allocation of responsibilities across various tiers of government, from national to local levels [65, 70]. Transition management requires involvement of actors from multi-layer networks and different institutions [48, 67, 70].

Case study setting, materials and methods

In this case study, an energy transition pathway model was created for the City of Helsinki employing energy system modeling, environmental and economic assessment, and transition pathway co-creation. The City of Helsinki aims at carbon neutrality target by 2030 and zero-carbon target by 2040 [71]. In 2022, the local energy utility Helen Ltd, which is solely owned by the city, still produced 63% of the district heating with coal and 10% with

gas and oil [72]. District heat covers >90% of all heat consumed in Helsinki.

The City of Helsinki controls local zoning and permitting processes, and owns the local energy utility, large land areas and many real estate companies with large building stocks. Helsinki organized the Helsinki Energy Challenge competition in 2020–2021 to identify solutions, such as technologies, operating models, and policies, which would enable phasing out coal by 2029 and to reach –80% emission reductions from the 1990 levels by 2035 in the local district heating system by using as little biomass as possible [56, 57]. Helen Ltd. is expected to deliver economic profits to the city, and to meet carbon neutrality goals set by the city simultaneously [27].

As a municipal energy utility, Helen Ltd manages the local district heating production and network assets. In 2022, the heat production capacity consisted of heat pumps (0.25 GW_{DH}, gigawatts for district heating), coal combined heat and power units (CHP, 0.7 GW_{DH}), natural gas combined cycle units (NGCC, 0.6 GW_{DH}), heat only boilers fired with biomass (0.1 GW_{DH}), gas (0.6 GW_{DH}), and oil (1.6 GW_{DH}). The heat pumps function as year-round baseload units. Large coal CHPs, NGCC units, and biomass boiler operate during the heating season depending on the prices and taxes on each fuel. Flexible gas boilers handle quick demand changes, such as the surge in heating during cold weeks and hot water needs on weekday mornings. Oil boilers are reserved for peak demand periods to ensure supply–demand balance and to offer backup in case of failures.

Energy, economic, and environmental modeling

Energy system modeling was undertaken to evaluate the required investments for the new capacity for meeting the City of Helsinki's climate target within its district heating system. The Helsinki metropolitan area district heating and cooling model [12, 73, 74] was adapted to this analysis by updating input data, including neighboring cities' interconnected district heating systems and foreseeable investments across the region, such as Helen Ltd's investments in the pipeline consisting of expansions of existing heat pumps, a large heat storage, and 250 MW_{DH} (megawatts for district heating) of bioenergy units. The data consisted of open energy data [75] including a detailed report on the heating system in Helsinki with key facts and figures, a map of Helsinki district heating network and data of fuel prices, electricity prices, taxes, and emission prices. Furthermore, specific data was collected of the existing energy production units in Helsinki, such as their capacities, efficiencies, operation, and maintenance costs, [76–78] and of new technologies to model future investment options [79]. In the modeling, biomass-based generation was excluded as an option for new capacity due to Helsinki Energy Challenge's instructions to avoid the increasing use of the biomass, and nuclear district heating because of estimated schedule of commercial projects until 2030s or late 2030s. The model covered investments and operations of the studied systems by taking into account both operational and investment costs while maintaining energy balances, operational limits of units and networks, required reserve capacities, storage dimensions and equilibrium, as well as inter-grid transmissions [24]. All units producing or consuming electricity were assumed to operate on Nord Pool power markets selling or buying electricity with hourly prices. Decommissioning costs of phased out units were assumed to be 10% of the investment cost of similar new units. The model annualized investment and decommissioning costs with a 4% real interest rate and assumed a 25-year economic lifetime.

The climate impact assessment accounted for direct CO₂ (carbon dioxide) emissions from fossil fuel combustion and some indirect life cycle emissions. The Helsinki area's district heating and cooling model incorporated direct emission coefficients from [80] and indirect emissions derived from [81, 82], which covered fuel processing and transportation emissions but excluded changes in forest carbon stocks.

Additionally, the economy-wide, and natural resource implications of the new capacity investments were assessed by using the ENVIMAT model, an environmentally extended input–output model tailored to the Finnish economy [83, 84]. The model estimates total consumption of all domestic and imported raw materials required to manufacture the needed products and services along the production chain. The raw material demands for coal, natural gas fuels, and heat pump technologies were assessed. With values based on the structure of the Finnish economy in 2015, 66% of required raw materials were assumed to be imported and 34% of raw materials were assumed to be extracted from Finland for each 100 MW_{DH} of heat pumps (see Table 1).

Transition pathway co-creation

We sought to simultaneously achieve cost-efficiency, supply security, and social acceptability by defining transition pathway steps toward the climate target. This involved implementing resource-efficient technical solutions based on modeling results, while also ensuring social acceptability for local stakeholders. We co-created the transition pathway model as a multidisciplinary expert team in a series of fifteen meetings between August 2020 and January 2021. Our team (see authors) shared a variety of complementary expertise on electricity and district heating systems, low-emission technologies, modeling, energy and public procurement policies and regulations, energy markets, climate financing, investment feasibility assessments and energy governance structures and practices focusing on the energy transition toward zero fossil fuels. Experts from Helen, the City of Helsinki, and a consultancy company hired by the city participated as commentators in two meetings held before and during the competition. The purpose of these meetings was to ensure that all relevant technical aspects were considered in the planning of the proposed solutions, without discussing the solution proposals themselves. After the competition, a feedback session was held with representatives from the City of Helsinki and Helen Ltd, where the proposals were commented on.

We co-created the transition pathway for the City of Helsinki, partially following the flexible and adaptable Transition Management approach, while recognizing that transition is an iterative process [58, 59]. Interlinked transition pathway steps toward emission reduction target and modeled future energy scenario were developed. The city was considered as the main actor and facilitator of the district heating system decarbonization. Other key actors and their roles are outlined in Table 2 (see below).

We aimed at identifying effective and swiftly actionable measures, given that the timeline of the climate targets in 2035 was relatively short compared to the energy investment timelines. In the consecutive design of the heat auctioning scheme, the renewable electricity auctioning guidelines by [85] were followed by applying and modifying them concretely in the context of the Helsinki's heating market. The key difference between local heating auctions and typical electricity auctions was the consideration of capacity requirements to meet peak demand

Table 1. Estimated natural resource requirements to build each 100 MW_{DH} of heat pump capacity.

Raw materials	Domestic origin (%)	Estimated raw material requirement (million kilograms, Mkg) per 100 MW _{DH} of heat pumps
Metals	1%	53
Soil materials	97%	27
Fossil fuels	7%	14
Wood	79%	9.5
Construction minerals	31%	5.5
Industrial minerals	29%	3.1
Crops	49%	0.5
Total	34%	112 Mkg

Table 2. Key stakeholders and their respective roles in shaping Helsinki's district heating transition and Finland's heating market.

Key stakeholders	Roles
City of Helsinki	Provides governance, sets local climate policies, and oversees urban infrastructure, spatial planning and permitting processes. Owns Helen Ltd and several real estate and other companies.
Helen Ltd	Operates district heating and electricity grids in Helsinki; key player in implementing new technologies as a regional monopoly.
EU	Sets directives, regulatory guidelines, and funding opportunities that influence national and local climate and energy policies.
National government	Establishes the national regulatory framework, provides subsidies, and implements decarbonization policies.
Finnish Energy	Represents energy companies, advocates for policy changes, and gives binding recommendations for industry players.
Building and real estate owners	Implement energy-efficient and sustainable solutions in buildings.
Researchers and experts	Offer technical expertise and research to guide policies and best practices for the sustainable transition of heating systems
(Technology and third-party heat providers)	Potential suppliers of low-emission heat sources, though limited by Helen Ltd's regional monopoly.

during cold winter periods, along with ensuring appropriate geographical distribution. These factors were incorporated into the recommended auction criteria and contracts, with further refinements recommended for the auction design (see [86] for more details).

Post impact evaluation

Future implementation of the proposed actions was assessed based on the feedback received in the meeting organized by the City of Helsinki between award winning teams of the Helsinki Energy Challenge and experts from the City and Helen Ltd, and by reviewing the City of Helsinki's strategy and ownership policy documents which officially steer the city's climate program and companies. The data consisted of the meeting notes from the feedback session with City of Helsinki and Helen Ltd representatives in March 2021, and review of The Helsinki City Strategy for 2021–2025 [71], Ownership Strategy for Helen Ltd [87] and updated Carbon Neutral Helsinki Action Plan [88] in 2024.

Results

The results presented in this section build upon those introduced in the competition entry [86], complemented with detailed methods, references, and reflections on the research process. Here, the results of our analysis are presented by employing terminology from the energy transition literature and including reflections on the analysis process. This ensures that the results offer novel insights and contributions, contextualized within the academic discourse.

Technical solutions

According to the energy modeling results, the installation of 300 MW_{DH} heat pumps, utilizing thermal energy sources such as ground, geothermal, excess heat, sea water, and air, would be enough to phase out the coal and replace 60% from the used natural gas. As a result, direct and indirect fossil CO₂ emission from power and heat generation in Helsinki would decrease by 80% compared to 2019 levels. While operational costs would decrease by 2%, the overall annual costs would increase by 18% due to necessary investments and decommissioning costs. Further investment in additional 200 MW_{DH} of heat pumps would replace 10% of the used natural gas and 15% of the used biomass. Additional share of the natural gas. The cost structure would remain similar compared to 300 MW_{DH} investments due to a similar estimated cost level between heat pumps and biomass boilers.

The optimal heat pump capacity (200–500 MW_{DH}) depends on the success of the City of Helsinki's energy efficiency program to reduce the buildings' heat demand from the privately owned housing companies and other building owners [89]. If all efficiency improvements were realized as planned, the total DH demand would be reduced from 7 to 5.5 TWh. In the case of the most successful energy efficiency measures, only 200 MW_{DH} of new heat production capacity would be needed. However, the current trend in the Helsinki's DH demand is slightly increasing due to increasing population. If this trend would continue, then 500 MW_{DH} of new capacity would be required. We estimated that the new heating capacity would be most likely closer to higher end of the range, as the heat demand in Helsinki has not declined, and the program included only free advisory services and no fiscal incentives to reduce the heat demand.

Thus, this study highlights the need for other low-emission solutions, including lower temperatures in district heating networks to enable higher efficiency of heat pumps, demand response, smart control systems, and storage for additional flexibility, as well as low-emission synthetic fuels to reduce emissions from peak power units. These supportive measures are even more important because our modeling assumed that sufficient heat would be available for the modeled heat pumps. In reality, there may be capacity limitations for heat pumps, preventing the highest modeled capacities and requiring greater reliance on other solutions.

Other limitations of the energy modeling results were related to uncertainties of the specific unit costs, and of the future technology and price developments. It was not possible to define the exact cost order of the different heat pump applications, as the final costs are always project specific. Uncertainties in investment costs for different technologies are typically reasonably large due to varying maturity level of technologies, required investment schedules, significant local variations in labor costs, land availability, connection requirements to existing infrastructure, and the potential reuse of components from decommissioned units, such as DH connections, heat exchangers, and site facilities. We did not model sensitivity analysis on these factors, as the main focus of the proposal was on the auctioning model and transition pathway. However, we recognize that, due to these uncertainties, alternative technologies, such as small modular nuclear reactors, solar energy, fuel cells, electrolyzers, carbon capture, and methanation technologies, hybrid production units in buildings, energy storage, and geothermal energy solutions, could play a role in the transition pathway.

Ensuring security of supply is an indispensable part of the energy system development. To mitigate the foreseeable security of supply risks in Helsinki relating to heat and power production, we preserved the existing heating boiler capacity of ca. 2000 MW_{DH} in the modeling in addition to adapting new heat storages, demand response solutions, and expanded electricity transmission networks. The oil and gas heat boilers operate only 50–200 h annually, resulting in limited emissions while offering peak demand capacity, production adjustability, and backup for failures. Further studies are needed on the required capacity. As part of the final push toward zero emissions after 2035, the remaining oil and gas of the boilers could be substituted with biogas, e-methane, and other green synthetic fuels. To mitigate the risk of low power supply, large heat storages, and demand response solutions are crucial for balancing Helsinki's heat pump power requirements. On the coldest days, energy storages and automated demand response systems controlling buildings, electric vehicle charging, and heat pump systems may significantly reduce electricity demand. Improving building energy efficiency decreases the average heat load, which in turn reduces the operating hours of boiler units. The impact of energy efficiency measures on peak demand and the required boiler capacity should be further studied once more information is available on the success of these measures. Phasing out coal CHP and reduced use of NGCCs reduce local electricity production, while the expansion of heat pump capacity increases power demand. Thus, further extensions the electricity grids are needed.

Emission, natural resource, and economic impacts

The emission impact analysis confirmed that direct CO₂ emissions would decrease by 80% from 2019 to 2035, from 3.1 to 0.7 MtCO₂ by implementing presented technical solutions. This

reduction is primarily due to phasing out coal (–2.5 MtCO₂eq), decreasing natural gas usage (–0.4 MtCO₂eq), and a slight increase from more electricity purchased for heat pumps (+0.1 MtCO₂eq). The emission coefficient for district heating would fall from 200 to 60 gCO₂/kWh, with direct and indirect emissions dropping from 250 to 90 gCO₂eq/kWh. Additional emission reductions should arise from reduced use of biomass, but those were not included in our modeling.

According to the natural resource modeling, replacing fossil fuels with heat pump solutions would achieve net reduction in use of natural resources: the amount of replaced fossil fuels by 2035 equals roughly to 930 000 tons of coal and 170 000 tons of natural gas each year. In comparison, investing in 300 MW_{DH} capacity of heat pumps would require 336 000 tons of raw materials in total.

According to economic modeling, replacing coal and natural gas would stimulate the economic activity in Finland: the investments in heat pumps would increase economic output, municipal and government tax revenues, and employment impact during the investment phase especially in the construction and mechanical engineering sectors, and administrative and other business support activities. Implementing 300 MW_{DH} of heat pumps would boost economic output by 306 million euros (in 2020 real prices), encompassing both direct and indirect effects. This would result in a value-added increase of 125 million euros and create nearly 1900 job opportunities during the investment phase. The overall power and heat system costs would increase only 10% from the 2019 levels.

Transition pathway actions

In the process of reflecting how the city could assure that the local climate target is met, we concluded the city should establish an executive committee to manage the transition, implement clean heating auctions, create an open energy map, and introduce fast-track-permitting processes as key transition pathway steps (see Fig. 1).

Through the combination of these measures, we estimated it would be possible to maintain stable heating costs in Helsinki while ensuring required investment volumes and social acceptability by the local stakeholders. These activities would enable third-party inclusion to the district heating network with the aim to improve the social acceptance and the adoption of the distributed low-emission solutions. We recognized that district heating companies' pricing and production models have not been incentivizing much local enterprises, housing companies, and building owners to invest in clean heating production, demand response, energy efficiency improvements, or heat exchanger renovations for lowering the network temperatures. As the City of Helsinki owns fully the local energy utility (monopoly), the city could enable third-party access and two-directional heating networks, and to steer the company toward developing, piloting, and offering new contract types for the customers to incentivize emission reduction activities.

As developing technologies and other evolving factors influence the cost-efficiency of the investments, we concluded the transition pathway model would need to be flexible, iterative, and reflexive to adapt to the specific investment conditions and changing markets and technologies during the transition. An executive committee would be established to manage the transition with clearly defined decision-making power, mandate, and expertise to achieve emission reduction goals. During the transition period, the executive committee would coordinate and monitor investments, update energy models, evaluate progress and

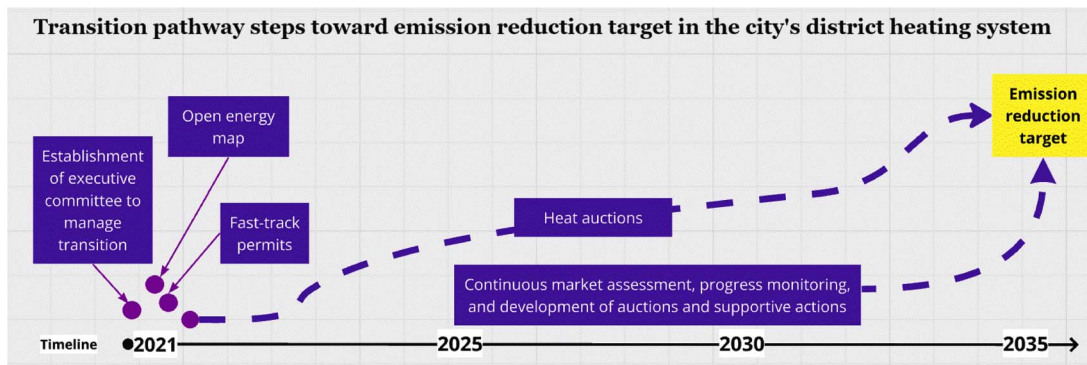


Figure 1. City's transition pathway with continuous development activities.

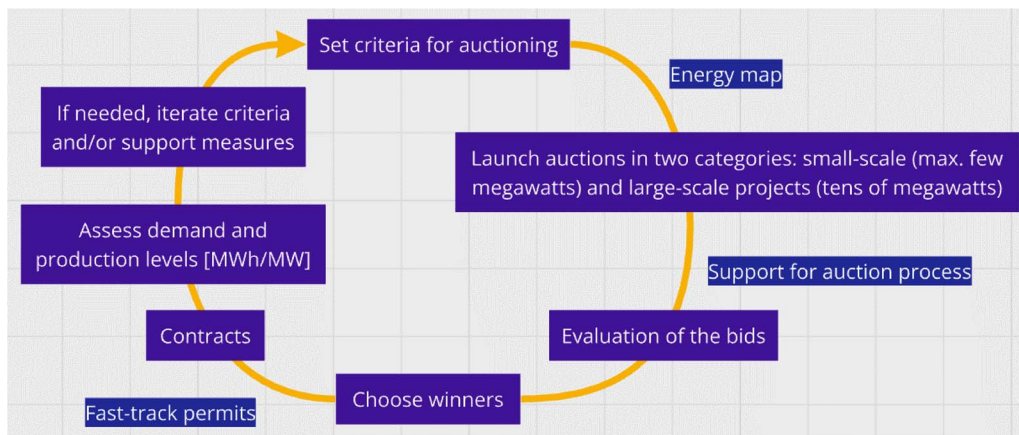


Figure 2. Clean heating auctioning process and implementation cycle.

barriers, and develop further improvements to regulations and incentives in cooperation with key stakeholders. The zero-emission transition requires a comprehensive approach involving multiple policy, market, and business model reforms, which necessitate multi-stakeholder cooperation to manage complex processes and align diverse emission-reduction measures within the broader energy system context [11, 49, 90–92]. The committee's role would be crucial in facilitating these efforts and ensuring cohesive action.

The clean heating auctions were included to tackle the challenges of uncertain investment conditions, as the auctioning enables the identification of the most cost-efficient combinations of sites, actors, and technologies [93–96]. To succeed with the required capacity investments of 200–500 MW of heat pumps to achieve the emission reduction target in Helsinki by 2035, more actors and investors are likely needed than the local energy utility alone, and thus auctions would promote the network access for the third parties.

The heat auctioning process, as illustrated (see Fig. 2), begins with setting auction criteria and organizing auctions in two categories: one for on-site producers in buildings and another for large-scale clean heat producers. After the bids are submitted, they are evaluated, winners are selected, and contracts are awarded under the support scheme. This is followed by ongoing progress evaluation.

The auctions could start with smaller volumes to prevent bottlenecks in supply chains and then progressively increasing the auctioned capacity volumes in a predictable and transparent way, enabling the market actors to adapt and respond gradually to the escalating demand.

The auctioned volumes and eligibility criteria could be adjusted based on the continuous progress monitoring, evolving market conditions, and advancement of technical and service solutions. The city as the organizer of heat auctions would pay for the winning bidders the difference between least-cost auction bids and Helen Ltd's openly published, seasonal purchase prices. This way, the city administration could implement the auctions in accordance with the Finnish public procurement laws.

The auctions would be essentially technology-neutral, although environmental and quality criteria could be established to ensure specific outcomes related to capacity, emission reductions, supply security, biodiversity, and social equity. For instance, unsustainable biomass could be excluded. In situations where heat supply challenges are anticipated, the auctions could be adapted to incentivize demand response, energy storage, and peak production investments, as challenges in the electricity supply could rise if these solutions are not in place in advance. Thus, the heat auctions could pull new heat capacity around the city and furthermore require the adoption of flexibility solutions ahead of removing the CHP units. There could be also contractual requirements for the producers to provide heat with full capacity in the coldest hours of the year even if it would not be economically feasible.

The proposed fast-track permits and an open energy map aimed at reducing bureaucracy bottlenecks and project costs. Fast-track permits would allow building of distributed production with, for instance, quick notifications instead of slow application procedures. Open energy map would visualize heating network connection points and suitable land areas for distributed heat production units, such as allowed plots for drilling boreholes,

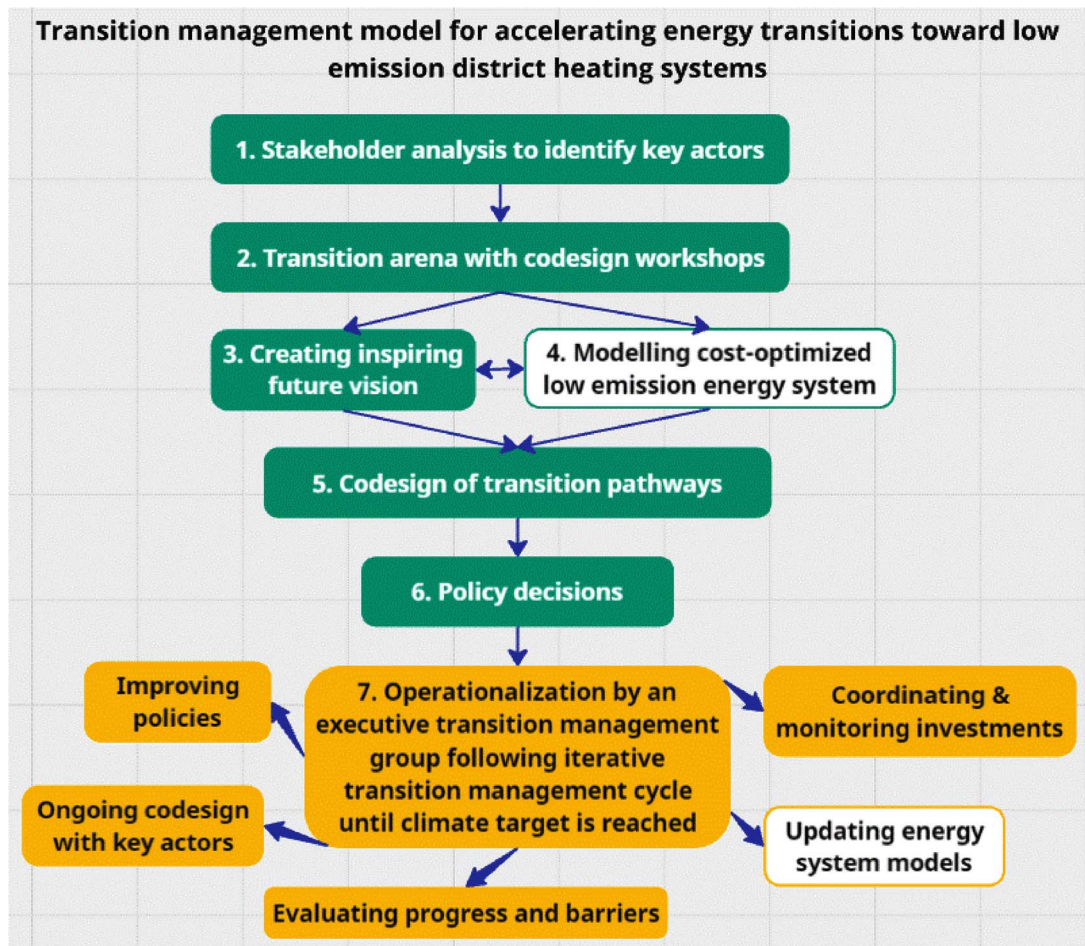


Figure 3. Urban transition management model for zero-emission district heating systems, adapted from [59].

installing solar panels and building storage systems. The network connection points and terms to both supply and return pipes would be classified according to different temperature and energy output levels. Aiming to lower network temperatures and increase the feasibility of low-temperature heat sources with heat pumps, the goal is to facilitate the transition to fourth-generation district heating systems (4GDH), which operate without fossil fuels by relying on renewable energy, excess heat sources, heat storage, two-way heat connections, and reduced building heat demand [4, 19, 97].

By 2024, the City of Helsinki had not official plans to adopt or implement these transition pathway steps.

Discussion

The Urban Transition Management Model for Zero-Emission District Heating Systems (see Fig. 3) was constructed upon the Transition Management Framework [59] by incorporating lessons from our case study and related literature.

In the model, first step (1) is the stakeholder analysis to identify key actors prior to organizing the (2) transition arena with policy codesign workshops. In step (5) transition pathways are co-created based on the (3) future vision and (4) cost-optimized zero emission energy system modeling. Then, the policies and other measures outlined in the transition pathway, proceed toward implementation through (6) the decision-making and (7) establishment of executive transition management group which operationalizes

the transition activities in an iterative way until the zero-emission district heating system is achieved. In the following, energy system modeling, policies and operationalization of the presented model are discussed more in detail.

Energy system modeling

Reflecting on our energy analysis applied to local district heating system, it becomes clear that defining actions based on energy system modeling is essential. This approach ensures cities can simultaneously secure sufficient heat supply, achieve cost-efficiency and accelerate rapid decarbonization. Currently in cities urban and energy planning are usually under the responsibility of different departments or organizations, but their integration is required to reach climate goals and to swiftly accommodate distributed energy systems in local spatial models [98]. The transition management studies often highlight the importance of compelling visions for developing transition pathways, and argue that social and motivational dimensions should be better considered in future visions to avoid strategies of becoming too technocratic [45, 99]. Too narrow focus on energy model scenarios, least-cost pathways, and techno-economic dimensions have been criticized for overlooking the importance of public engagement, social acceptance, and political feasibility [45]. We consider that energy system models should complement such more inspiring future visions by giving technical, economic, and environmental orientation to the pathway building. The formulation of compelling but specific visions and

scenarios can effectively guide transition pathway building toward transformative changes [99, 100]. Energy models are crucial for investment and policy development for various reasons. Given the large complexity of an energy system and due to the decentralized character of renewable energy sources, systemic energy planning is fundamental to properly manage the local system development and for ensuring a sustainable, affordable, and reliable energy mix [21, 28, 101, 102]. The decarbonization of the energy system is a very complex process, where a wide variety of measures need evaluation and coordination in the context of the entire energy system considering the cross-sector synergies between buildings, industry, traffic, heat and power generation, and energy storage solutions [11]. In the district heating systems it is important to consider the interactions and dynamics of the production units, buildings and other system components when designing strategies and policies to support the energy transition in both the production and heat user sides [10, 101]. The pathway toward fully decarbonized society requires politicians, civil servants, and companies to prioritize energy solutions which fit well into the future zero-carbon system [11, 92]. Energy model scenarios do not stand alone as future visions for developing transition pathways toward zero emissions but are needed to guide technical reconfiguration of the district heating systems. Inspiring, compelling, and co-created future visions are essential tools for transition management, as they tap into actors' motivations and provide cognitive and emotional anchors that guide change and collective action [47, 62, 103, 104]. Visions of sustainable cities, for example, go beyond technical models by appealing to people's desire for a cleaner, healthier, and more equitable environment and society.

Policies

Cities can play a key role in accelerating local energy transitions through policies in an inclusive way to improve social acceptance. Heating auctions could ensure cost-effectiveness to decarbonize district heating systems in rapidly developing energy markets and pave up the path to carbon neutral cities in a flexible way. When the city is the owner of the local energy utility, it can adopt several policies to decentralize heating markets, reduce costs and to improve third-party market access to accelerate the expansion of low-emission heating investments. Based on careful consideration of local economic, regulatory, and corporate ownership arrangements, we proposed the city of Helsinki adopt several measures, such as heat auctions, open energy map, and fast-track permits, to accelerate the expansion of low-emission heating investments. Furthermore, we proposed the establishment of an executive committee to manage the local energy transition in an iterative and reflexive way. In principle, the transition research justifies the necessity of this kind of measures, but also highlights their implementation challenges. According to research, the policies are critical to deliberately accelerate transition toward decarbonized energy systems [92, 95, 105]. A coherent set of market creation policies and measures are needed to engage companies and other actors to adopt new technologies and to reconfigure persistent business and administrative practices in the established markets [30, 65]. Policies which have been already adopted to support district heating modernization include, e.g. grants and subsidies, fossil fuel and emission taxes, renewable heating and cooling targets, zoning policies, building standards, and consumer protection rights [10]. In addition, researchers have called for renewed jurisdiction to allow companies, buildings and other third

parties to access heating networks as prosumers, and to streamline administrative procedures and public permitting processes [37, 40, 106, 107]. For improving third-party access to district heating systems, measures such as one-sided auction on the supply side has been presented by [35], pool and peer-to-peer market designs by [33], and new heat supply contract models between district heating companies and excess heat providers have been proposed by [108]. We proposed heating auctions, as there is vast experience and body of knowledge of proven effectiveness of auction designs from the electricity sector, which have successfully increased renewable energy production in a cost-efficient manner [94–96]. Despite such proposals, not much progress has been reported to improve third-party access in a required scale to accelerate the expansion of low-emission investments in the district heating systems.

Implementation

Finally, we reflect on factors why our proposal has not been adopted for implementation although it was awarded in the Helsinki Energy Challenge competition [109]. Based on the feedback received from representatives of the City of Helsinki and Helen Ltd, heat auctions were not a suitable fit for the operational framework of the City of Helsinki and were incongruent with Helen Ltd.'s business and investment models, primarily due to the inclusion of subsidies for third-party access. Reflecting on the literature on sustainability transitions, we highlight two highly apparent implementation barriers. First, the heating auctions challenged the current operating models of the key regime actors: the local energy utility and the city as a public administration organization, which owns the local energy utility and receives its equity incomes. Third-party access has been identified as a threat for the monopoly of district heating companies, as a competing heat vendor can cause them revenue losses [34]. Incumbent regime actors often oppose disrupting changes that challenge their operating models and roles [30, 110]. Second, the transition pathway model was developed by a small group of experts without involving decision-makers. Co-creation has been recognized as an important success factor in the facilitation of low-emission energy transitions in regional and local contexts [39, 70, 111]. Some successful energy transition outcomes have been achieved from strategic intermediation processes between numerous actors to legitimize and implement the market shaping policies [30, 70]. "Wicked" problems such as climate change cannot be addressed without multidisciplinary collaboration and joint problem solving, which are critical to operationalize and to accelerate energy transitions in democratic societies [65, 67, 92, 112]. Policy planning and implementation during the energy transition requires multi-level governance and close coordination among several government ministries and local authorities [42, 65]. For broader societal buy-in, the transition pathway co-creation should be participatory so that policies are identified and discussed with decision-makers from e.g. energy utilities, finance sector, political parties, and other powerful actors involved in the energy transition [48, 65, 112]. In such a process, energy system modeling is crucial to support the key actors' salient decision-making based on understanding of the decarbonization implications across energy system [11, 113]. Therefore, it can be questioned if a competition such as the "Helsinki Energy Challenge" is a feasible way to find solutions to decarbonize district heating systems. The competition setting makes transition pathway co-creation with decision-makers very difficult or even impossible.

Conclusions

Large cities which own their local district heating utilities, have potential to accelerate the decarbonization of the local heating systems when they combine their authority roles and financial capacities. Many big cities have power and possibilities to create enabling market conditions and policies for upscaling low-emission investments to phase out fossil fuels from the district heating systems.

Heat auctions can be used to boost required clean heating investments. Governments worldwide have widely used auctions to reduce emissions and create markets for new technologies and infrastructures in the electricity and transport sectors. Thus, we recommend further studies and experiments on how auctioning could be designed and implemented to decarbonize local district heating systems.

There is a lack of progress in emission reductions across district heating systems globally. Our energy system modeling in the Helsinki metropolitan area revealed the need for massive investments in low-emission solutions in a relatively short time. To meet the Paris Climate Agreement targets, there is an urgent need to turn decarbonized energy system models into transition pathways and concrete implementation of strong policies and measures. The pathway toward fully decarbonized society requires energy modeling to guide technical reconfiguration of the energy systems, and to instruct politicians, cities, and companies to scale-up investments to solutions which fit well into the future zero-emission energy systems.

These transitions demand that regime actors adopt new institutional roles, business models, redefine market structures, and regulations, which is highly challenging to achieve.

An increased effort is required to develop processes that facilitate the adoption of novel policies, operational practices, and business models, especially within the complex governance landscapes involving multiple actors with tendency to resist transformational changes. Decarbonizing energy systems requires synchronized efforts and investments from various actors. Cities stand in a crucial position to act as facilitators, funders, policy-makers, and navigators of local energy transitions toward zero-emission district heating systems.

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Author contributions

Karoliina Auvinen (Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Methodology, Software, Validation, Visualization, Writing—original draft), Tomi J. Lindroos (Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing—original draft), Åsa Hedman (Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Writing—review & editing), Hannu Savolainen (Data curation, Formal analysis, Investigation, Methodology, Software, Writing—review & editing), Alekski Lumijärvi (Conceptualization, Data curation, Investigation, Validation, Writing—review & editing), and Pasi Tainio (Conceptualization, Data curation, Investigation, Validation, Writing—review & editing)

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Data availability

Helsinki energy system data is publicly available at City of Helsinki website at: <https://energychallenge.hel.fi/heating-helsinki-today>. More detailed modeling data are available on reasonable request to the corresponding author.

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