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Municipalities as key actors in the heat transition to decarbonise buildings: Experiences from local planning and implementation in a learning context

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ABSTRACT

Municipalities are key actors in planning and enabling the transition in the built environment to sustainable heat systems. Literature on the municipal experiences in the early phases of the heat transition is scarce. This paper addresses this gap by depicting the approaches of twenty-eight municipalities in the Netherlands. It aims to assess the municipal approaches to data collection, technology choice, and area prioritisation during the planning and (early) implementation stages and the barriers municipalities face. Identifying and choosing the optimal solutions per area requires numerous data, in-house knowledge and societal support. The lack of municipal capacity and know-how has led to a strong dependency on external expertise. District heating networks and heat pumps are presently seen as the most promising alternative systems, while building improvements are planned in areas when the technological choice is uncertain. Two important lock-in effects have hampered the local efforts to execute projects: a lack of binding policies to terminate natural gas use and poor affordability of the alternative heating systems. An overarching lesson is that the timely establishment of these aspects is critical to support the starting phase of the transition and that effective local governance cannot be achieved without centrally-established supportive mechanisms.

1. Introduction

Fossil fuel-based systems dominate heating in European buildings (Bertelsen and Vad Mathiesen, 2020) and the potential for improving energy efficiency and integrating renewable energy sources in existing buildings is significant (Djørup et al., 2019a). Nevertheless, the decarbonisation of heating systems in existing buildings (hereafter 'the heat transition') has been somewhat overpassed, and other areas such as renewable electricity production have gained more attention (Büchele et al., 2019; Bush et al., 2016; Connolly et al., 2014). Although this trend is changing in the past years with several initiatives and European climate policies for heating (Honoré, 2018; REN21, 2016; van de Vyver et al., 2020), the complete decarbonisation of heat supply in buildings is far from straightforward. Sovacool and Martiskainen (2020) indicated that the systems bring significant investments without delivering a much higher service from the consumer's perspective. Second, it is a socio-technical transformation requiring changes in existing long-lived infrastructures and social habits. Third, it demands new planning forms and multiple actions by different actors, scales and disciplines.

Given the local character of heat, municipalities are primary actors in driving the heat decarbonisation of buildings (UNEP, 2015; van de Vyver et al., 2020; Weinand, 2020) and in the implementation of national policy into local action (Bulkeley et al., 2010; Fenton et al., 2015; Hoppe and van Bueren, 2015). Local authorities are the closest organization to citizens and local actors (Coenen and Menkveld, 2002), two critical groups as many decarbonisation measures need to be realised in the private domain (Rodhouse et al., 2021). Local governments support, coordinate and co-create local efforts and provide resources and services (e.g. land, infrastructure, permits, and financial means) (UNEP, 2015).

Studies on municipal heat planning and implementation have been skewed towards the implementation of district heating (DH) systems (Busch et al., 2017; Chittum and Østergaard, 2014; Djørup et al., 2019a; Galindo Fernández et al., 2016; Harrestrup and Svendsen, 2014; Pol and Schmidt, 2015; Werner, 2003), which is only one of the potential technologies to decarbonise heat (Section 2). Also, greater attention is paid to regions with a consolidated history in alternative heating systems and a high level of local autonomy such as Denmark and Sweden

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Acronyms

DH	District heating
HP	Heat pumps
HT	High temperature
LT	Low temperature
MT	Medium temperature
NG	Natural gas
PAW	Programma aardgasvrij wijken (in Dutch) or Natural gas-free districts grants program

(Chittum and Østergaard, 2014; Damsø et al., 2016; Harrestrup and Svendsen, 2014; Krog, 2019; Krog and Sperling, 2019; J. S. Nilsson and Mårtensson, 2003; M. Nilsson et al., 2020).

Although these studies offer a handful of insights on how municipalities strategically plan, operate and modernise their heating systems in buildings, they are limited in disclosing information on the municipal experiences during the early and preparatory phase of the transition. The approach and potential complexities municipalities might face during the early phase deserve further analysis. Considering the growing interest in low-carbon heating worldwide, mapping municipal practices in this undeveloped and learning environment can provide useful guidance for governments in other regions following a similar transformation in the future. This paper addresses this gap by focusing on the experiences of Dutch local governments. The Netherlands is chosen because it is a country which recently started an ambitious transformation of its heat system and where the central government delegated heat planning and execution to municipalities in 2018 (Studiegroep Interbestuurlijke en Financiële Verhouding, 2020).

The municipal experiences in the Dutch heat transition have been addressed by grey literature and few academic papers, illustrating several governance challenges at local and national level. Tigchelaar, Winters, et al. (2019) studied the decision-making for large municipalities depicting the obstacles when developing new DH networks. The research outlines the great diversity in the approach used due to unique local circumstances and the dependency of the local government on the knowledge and expertise of existing DH suppliers. There is a need to equip municipalities with objective information and knowledge and offer affordable low-carbon heating solutions (Tigchelaar et al., 2019). The municipal challenges to implementing heat policy ambitions are further elaborated by van de Vyver et al. (2020), Diran et al. (2020) and Diran and van Veenstra (2020), underlining sub-optimal staffing in municipal teams and significant data gaps. They also highlight the need for compatible regulatory frameworks and financing mechanisms to unlock the implementation of renewable heating projects at the local level.

These studies suggest the complexity of the existing framework conditions in the heat transition and that this is more than ‘just another’ challenge. Our work looks at the novel responsibility of local governments in the Dutch heat transition and analyses the multiple barriers encountered in the process. We add to the literature on the Dutch heat transition in three ways. First, our study brings empirical examples of a large number of municipalities, as the attention up to now is directed to a few large, front-running cities – see, for example (Diran and van Veenstra, 2020; Tigchelaar et al., 2019; Tigchelaar et al., 2019; Woestenburg et al., 2020). Little is known how small and medium-sized municipalities or governments without previous experience tackle this challenge. This group is vital as small and medium-sized municipalities represent 91% of Dutch local governments and 63% of the population (Ministery of Interior and Kingdom Relations, n.d.). Second, the research analyses a few key elements during the planning and (early) implementation stages: the municipal approach to data collection, technology choice, and neighbourhood prioritisation (Section 2). Third, our work adds new empirical evidence of the local governance challenges during the realisation of heat decarbonisation projects.

Two goals guided the study:

- To explore how and under which conditions different low-carbon heat strategies are developed at the municipal level during the planning and early implementation stages;
- To identify the key challenges experienced by local authorities during this process.

In the next section, we provide a deeper insight into the Dutch heat transition, the scope of municipal plans and the planning instruments used. These elements and the governance barriers discussed above form the basis of the analytical framework in the following methodology section.

2. The Dutch heat transition and the scope of municipal strategies

The Netherlands has a competitive and stable NG provision where 90% of households use individual natural gas (NG) boilers (EuroStat, 2020). The Dutch Climate Agreement in 2018 established that the 8 million existing buildings would be progressively disconnected from the NG grid until 2050 (Ministry of Economic Affairs and Climate, 2019). The Agreement states that adopting alternative heat systems needs to be cost-neutral. For citizens’ acceptability, the alternative systems must not exceed the costs a household would have borne when using NG (Rodhouse et al., 2021).

The Dutch heat transition is being organized locally, and municipalities have been given great responsibilities in coordinating and executing heat projects. Given the complexities of the heat transition outlined in Section 1, the national government has developed several institutional and regulatory instruments to support local governments. The Heat Expertise Centre provides information and capacity building to municipalities regarding techno-economic, legal and organizational aspects. The ‘NG-free districts’ grants program (in Dutch and hereafter ‘PAW’) (Rijksoverheid, n.d.) has given financial support since 2018 to decarbonise heating in selected communities. It is designed to offer experimental space and gain socio-technical expertise for later upscaling. Last, on the regulatory front, new legislative changes for the DH market are being developed to facilitate the roll-out of DH as current regulations are outdated.

Each municipality needs to develop a heat transition strategy by the end of 2021, after which implementation plans must be drafted for each area (Wiegerinck, 2020). The initial municipal strategy comprises two main building blocks assessed in the present paper: i) to identify potential low-carbon heating systems per area and ii) the identification of prioritised neighbourhoods to start decarbonising before 2030.

Municipalities strive to encourage and enable the uptake of various measures such as energy savings, heat pumps (HP) and DH networks. Three main low-carbon heat systems can be followed: centralised, decentralised, and in-between configurations (Fig. 1). Each of these routes entails different supply temperatures and thus building insulation levels. Typical high temperature (HT) sources and medium temperature (MT) are biomass, industrial residual heat and geothermal. Low temperature (LT) sources are solar thermal, waste heat (e.g. from data centres, swimming pools) and aquathermal energy.[1] MT can also be obtained when LT sources are upgraded using, for instance, a HP. Decentralised systems are either electricity-based heating technologies using air- or ground-source HP or electric boilers or based on renewable

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[1] Aquathermal energy refers to a water-source central heat pump extracting heat from natural water basins and (waste) water treatment processes. Aquathermal energy is often used in combination with seasonal storage (Aquifer Thermal Energy storage – hereafter ATES).

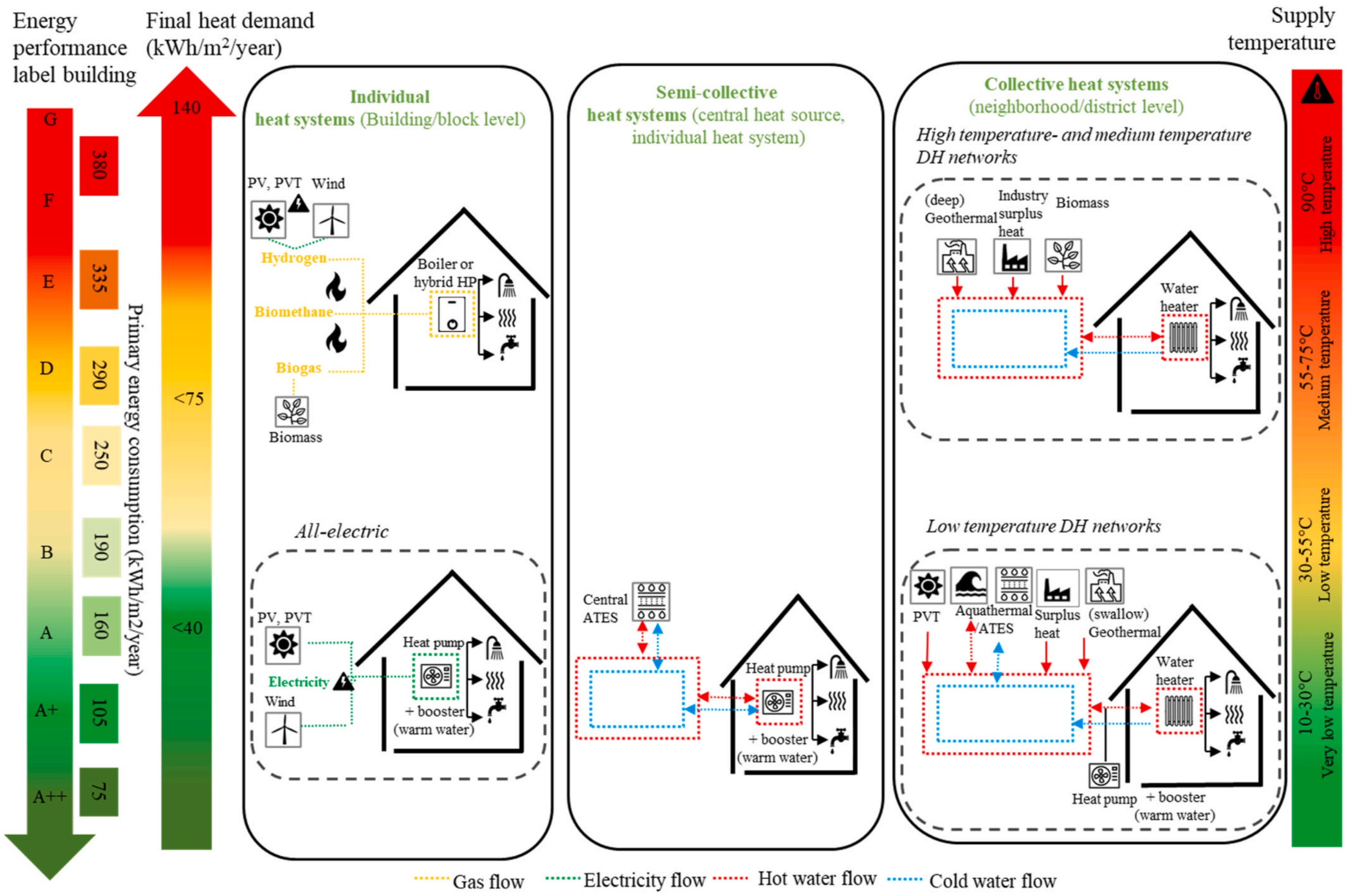

Fig. 1. Potential centralised and decentralised heating supply technologies. Required building insulation level and associated final heat demand (left) and supply temperature (right). Own figure with data from Verduijn (2021).

gases (e.g. biogas, hydrogen). In-between configurations combine MT- or LTDH systems and use an individual heating technology to boost the temperature.

Local planners must adopt solutions to the specific local conditions like the buildings' insulation level, the availability of heat sources, and the consumers to be supplied (Djørup et al., 2019a). The literature search for academic papers on municipal heat planning revealed that the process usually starts with constructing technical scenarios using heat mapping exercises. This step allows the assessment of the energy infrastructure, available and future heat density (i.e. heat demand per area) and available resources (Djørup et al., 2019b; Stremke & van den Dobbelsteen, 2012). This can help decide which areas are suitable for collective or individual systems. Heat savings options are also important to reduce fuel consumption and assess the cost efficiency of heating options, which is dependent on building insulation levels. These mapping exercises are crucial in the early phases of heat planning, as they will frame the alternatives considered further in the process (Djørup et al., 2019a).

Different planning instruments and tools can be used to carry out the heat mapping exercises. In the early stages, when there is very little information available for a given area, simple tools (e.g. geographical information systems) can map heat density and provide a first indication of the feasibility of the heating system (Pol and Schmidt, 2015). There are more advanced models for the simulation and optimization of these systems - see, for example, the techno-social ecosystem proposed by Diran et al. (2020) and the models reviewed by Diran and van Veenstra (2020). Energy system analysis and models are pivotal components of heat and energy planning, but obtaining the necessary data and performing the analyses can be challenging tasks for municipalities (Diran and van Veenstra, 2020; Henrich et al., 2021; Rasmus Magni Johannsen et al., 2021). The Dutch government developed its own open-source model to support municipalities in the decision-making of the heat transition; the Vesta MAIS model (Hoogervorst et al., 2019), a spatial techno-economic model to identify and compare potential heating technologies in terms of system costs and emissions.

Next to heat mapping exercises, a complex set of decision-making procedures at an organisational level must be considered in the early heat planning phase (Djørup et al., 2019b). Pol and Schmidt (2015) shows that one of the main strategic decisions to be taken is the definition of the priority areas to implement the alternative heating system. For example, deploying DH systems can be encouraged through coordination with the energy refurbishment of buildings (Galindo Fernández et al., 2016), new area developments or existing areas undergoing general improvements (Pol and Schmidt, 2015). It seems, therefore, necessary that heat plans are well embedded within the general urban infrastructure development in which the heating system is to be developed, such as electricity, transport, telecommunication, and social developments (Pol and Schmidt, 2015). Although Dutch municipalities already integrate these aspects to define priority areas (Henrich et al., 2021), each municipality can determine the criteria for the prioritisation.

3. Methods

The research employs a semi-qualitative and a multi-case study approach to the experiences encountered during the municipal heat planning and implementation. This section explains the research design, the case study selection and the data collection and analysis steps.

3.1. Research design

The literature discussed regarding the scope of municipal strategies in the early phases of the heat planning (e.g. heat mapping exercises, choosing prioritised areas) in Section 2 and the governance barriers presented in Section 1 have provided the basis to build the analytical framework of the study (Fig. 2).

In a first step, data were collected concerning two main themes of the municipal heat strategy plans: i) *Heat mapping and assessment*, which refers to the approach and tools used for data gathering and analysis phases to identify heat demand and sources; ii) *Technology-, and prioritised areas selection*, which allows understanding the underlying factors in the municipal choices to draw a heat strategy regarding the technological choices and areas that will be decarbonised first. If existing, pilot implementation projects are studied to learn how municipalities transition from heat planning towards realisation.

In a second step, key challenges are identified to gain insights into the barriers that local governments face in their decision capacity and the realisation of decarbonisation projects. Attention is paid to challenges encountered during the first step of the research design and to exploring national- and local-specific barriers. National barriers focus on economic- and regulatory barriers, which are important framework conditions affecting the viability of the local projects (Djørup et al., 2019b; Galindo Fernández et al., 2016). Here we looked also at how public officials apply available information and instruments provided by the central government. The main instruments provided by the central government to perform the heat mapping exercises (Vesta MAIS model) and to support project pilots financially (the PAW subsidy program) are assessed. Local barriers focused on the capacity of the municipal team in terms of manpower and expertise, as this is identified as a problem in the reviewed literature of Section 1. Finally, the analysis findings bring several policy recommendations in Section 6.2.

3.2. Case studies selection

A case study approach is suitable to meet the goals of the present study as it allows a rich exploration and description of an empirical phenomenon (Yin, 2009). A multi-case study is often considered more compelling, robust, and reliable than a single-case study bringing higher representativeness of various projects (Yin, 2009). Choosing the appropriate case studies is critical to the quality and relevance of the study. The research seeks to cover with sufficient representativeness municipalities with different sizes, capacities and contextual situations leading to twenty-eight case studies (Table 1). Size was categorized by large municipalities (>100,000 inhabitants), medium-size (50,000–100,000 inhabitants) and eleven small municipalities (<50,000 inhabitants). Municipalities were located in eleven of the twelve provincial regions. Half of the investigated municipalities had their heat strategy plans finished at the start of the research, and the other half expected completion at the end of 2021. Some municipalities have already received one or two subsidies (~4 million €/application) from the PAW program to carry out pilots to start decarbonising the heat supply in part of their buildings.

Fig. 3 shows that a DH network is present in half of the case studies, primarily fossil-based. The building stock is relatively old (built before 1965), except for case studies 1 and 22 (Fig. 4). The share of rental homes in some cities represents more than 50% of the total number of dwellings. Many of them belong to housing associations.

3.3. Data collection and analysis

Semi-structured interviews were conducted with program leaders of each municipality actively involved in the municipal planning phase. Interviews were held between January and March 2021, lasted one and half hour each and were recorded. The questionnaire contained multiple-choice and open questions (Appendix A). The transcripts of the interviews were obtained using automatic speech recognition software (Kaldi, n.d.).

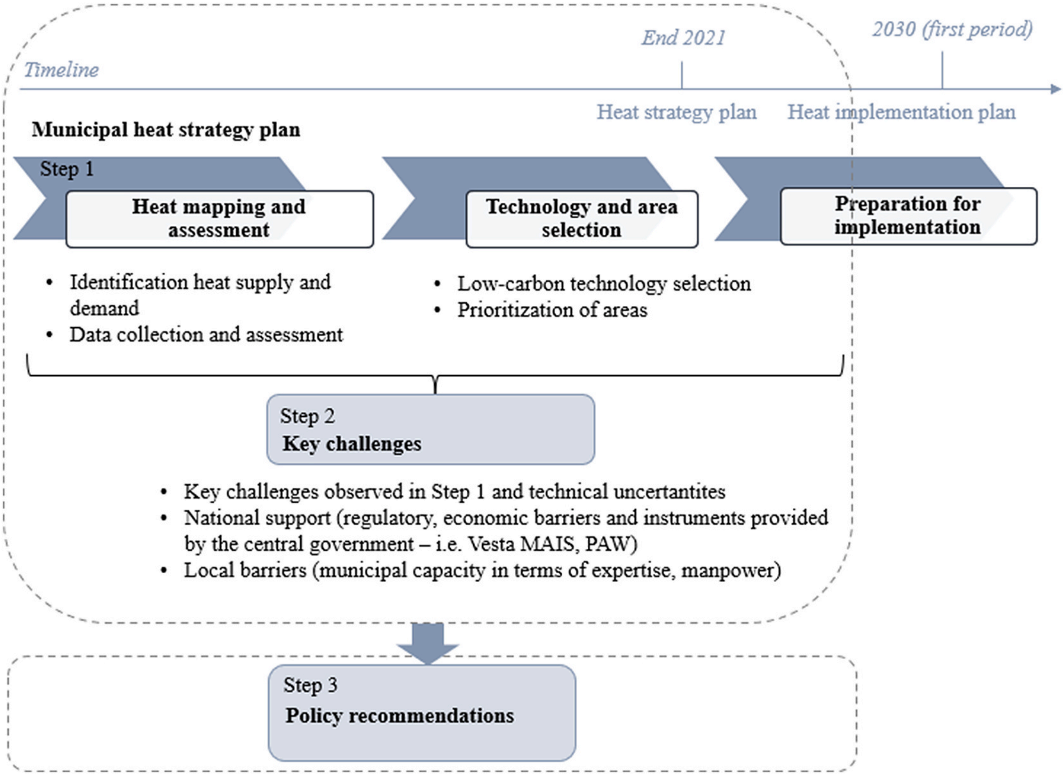

Fig. 2. Analytical framework and steps applied for data collection and analysis. In dotted lines, the scope of the research.

Table 1
Information describing the selected case studies. [a] The names of municipalities are omitted for anonymity reasons.

# Case study [a]	Size municipality	Region	Status heat plan document (as of 30 June 2021)		Number of awarded PAW subsidy	Target year heat supply decarbonisation
			In development	Ready (publication year)		
1	Large	Flevoland	▨			2050
2		Utrecht		(2021)		2050
3		Noord Brabant	▨			2040
4		Gelderland	▨			2050
5		Groningen		(2019)	2	2035
6		Noord-Holland		(2021)		2040
7		Zuid-Holland	▨			2050
8		Gelderland		(2018)	2	2040
9		Noord Brabant	▨		1	2040
10		Utrecht		(2021)	1	2050
11		Overijsel		(2020)		2050
12	Medium	Noord-Holland		(2020)		2050
13		Overijsel		(2020)		2050
14		Zuid-Holland		(2021)	1	2050
15		Utrecht	▨			2040
16		Friesland		(2021)		2050
17		Zeeland	▨			2050
18	Small	Drenthe	▨			2040
19		Utrecht	▨			2040
20		Gelderland	▨		1	2050
21		Gelderland		(2020)		2050
22		Utrecht		(2020)		2040
23		Utrecht		(2021)		2050
24		Noord Brabant	▨			2050
25		Friesland	▨			2040
26		Gelderland		(2020)	1	2040
27		Gelderland		(2021)	1	2050
28		Noord-Holland		(2020)	1	2050

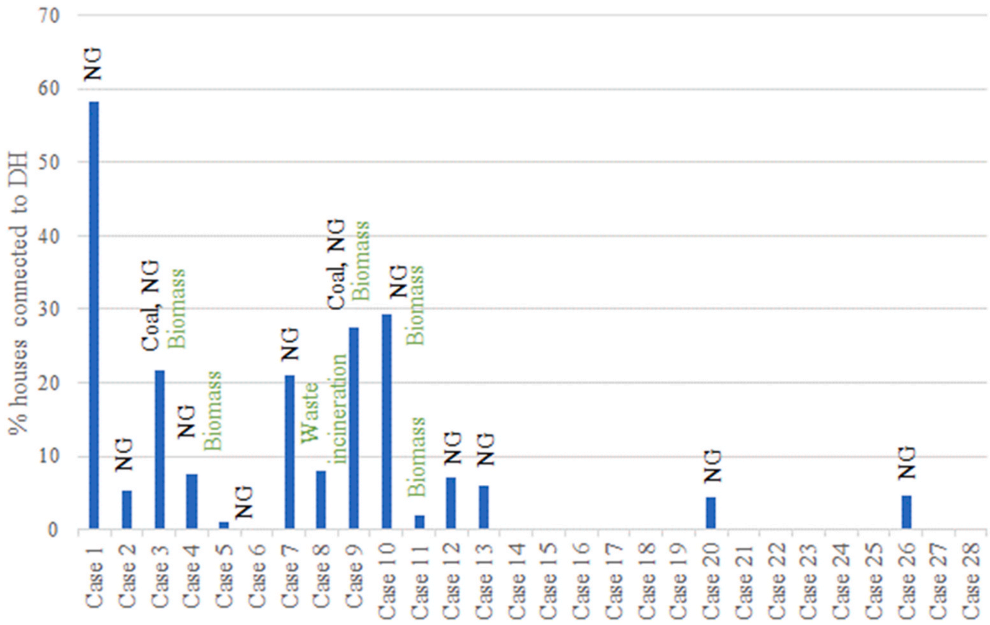

Fig. 3. Share of residential buildings connected to the existing DH network of the case studies and heat source used. Data from Vattenfall (2021) and CBS (2018).

Next to interviews, government documents were analysed, comprising the municipal heat strategies (if published), the regional heat strategy, and other relevant sources such as discussion papers, press articles, and other materials found on the municipality's website or from other organisations. Additionally, the latest legislative proposal of the national Heat Act (Overheid.nl, 2020) was assessed. Since the Heat Act proposal was placed in a public consultation in June 2020, an analysis of the 100 written reactions submitted by different stakeholders, including municipalities, was made to identify gaps and weaknesses in the proposed legislation from the stakeholders' perspective.

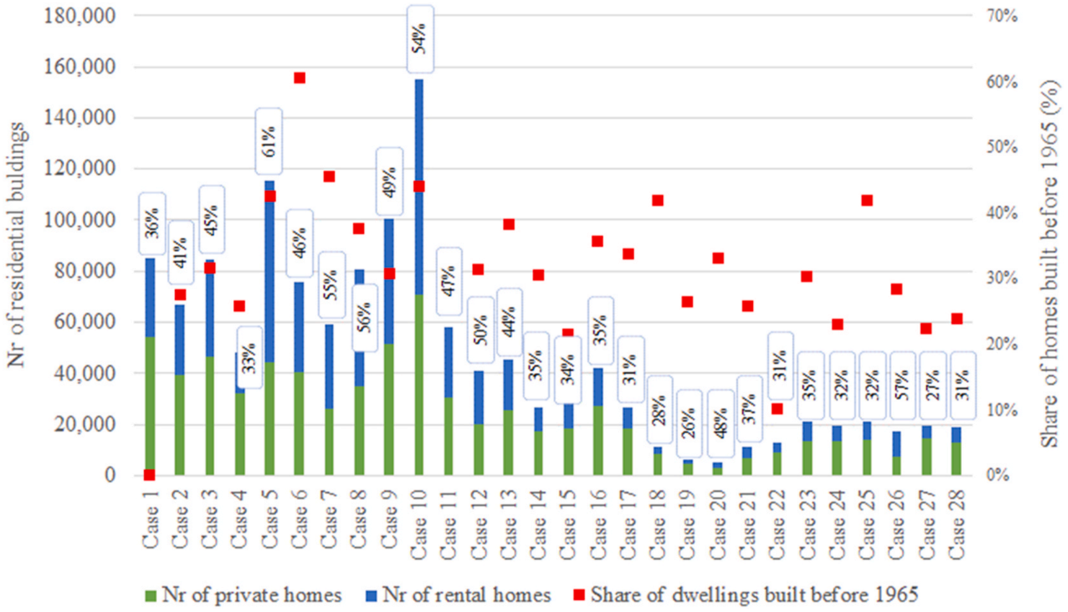

Fig. 4. Number of residential buildings and type of property owner (left axis), and share of dwellings built before 1965 of the case studies (right axis). In blue boxes the share of rental homes. Data from CBS (2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The gathered data was analysed by deductive and inductive coding. We started with a pre-defined code in line with the research design (Fig. 2), followed by a code set enriched with emerging codes derived from the empirical data. This process allowed the combination of codes that showed similarity and discharging rarely used codes. Interview data was validated by sending back the interview transcripts to the interviewees to scrutinize them.

The interview data were checked and complemented with literature (e.g. the written governmental documents and other sources) and worked collaboratively with a range of stakeholders who provided feedback to the study. The data were analysed with the software tool NVivo version 12 and later operationalized through a coding matrix. The operationalization allowed calculating the proportion of each analysed item with the sample size to quantify the characteristics of the assessed themes.

4. Results

This section presents the main findings in line with the themes of the analytical framework, starting with the data used during heat mapping and assessment, then the selected technical strategies and prioritised areas. Finally, the key challenges encountered during the heat planning and implementation are described. Note that challenges encountered during the steps of data collection, heat mapping and the selection and technical system and area are described within the corresponding section for ease of reading.

4.1. Data and approach used for heat mapping and assessment

Numerous data and investigations concerning techno-economic, environmental, social, and organisational aspects have supported municipalities in identifying potential heat options and prioritising areas that can decarbonise first (Table 2). This intense and interactive process requires constant adjustment when new and more updated information emerges.

Few municipalities have started building a database based on the available local, regional and national information. Besides the available databases that deliver the basic characteristics of their building-, spatial- and energy system, municipalities use the expertise and data available from their partners (e.g. network operators, housing associations, DH companies, heat producers and community-based initiatives). Obtaining information from partners is essential to gathering non-publicly available data and identifying possible restrictions and opportunities to align each other's plans.

Although most of the investigated municipalities (~75%) have used the national open-source methodology Vesta MAIS (available since 2019) and generally agreed it is a good starting point, it received several criticisms (see Section 4.4.5). Next to the national methodology, several Dutch consultancies have developed techno-economic models to advise the local governments on the best heat strategy. Nine of these models - which are not open-source - have been used by case study municipalities. A recent study (Brouwer, 2019) compared five models and the national methodology and concluded that the model outcomes differ. Therefore, it seems imperative to validate the results of the available heat models to identify robust heat strategies for specific neighbourhoods.

More than 80% of the heat-mapping exercises performed by the investigated municipalities have used the results of two or more techno-economic models as a starting point for their heat strategy. In all cases, further research was conducted to refine the results. The model comparison led to different heating technologies for specific neighbourhoods in eleven municipalities, where the most cost-efficiency solution could not be identified as a result of the different modelling techniques, the uncertainties in the potential of technologies (e.g., hydrogen, biogas) and area characteristics (suitable for various technologies). The municipalities have dealt with this problem by prioritising areas where the system stands out (i.e. 30% more cost-efficient than others) or refining the analysis at a smaller scale.

Fig. 5 shows the results of comparing the models and the positive impact of using a smaller geographical scale. These results have been obtained with a tool developed by a network operator (Stedin, 2021) that compare the outcomes of three available models, including Vesta MAIS. Fig. 5 shows the share of the buildings where a heating solution is robust regardless of the model used and the heat potential scenario. Two conclusions can be drawn. First, individual solutions such as HPs become more prominent at lower spatial levels as DH networks profit less from economies of scale. Second, the robustness of the technological choice applies to only 10% of the total building stock in most case

Table 2
Commonly used data by interviewed municipalities during heat planning (non-exhaustive).

Input data	Example	Data source	Used for
Building-related	• Building type • Construction year • Size • Type ownership (rental-, private- property) • Function (residential-, non-residential) • Building density • Theoretical insulation level • Present heating system • Opportunities to reduce heat demand	• Basic Registration Buildings and Addresses (BAG) • Dutch Statistical Bureau office (CBS) • Energy labels from Dutch Enterprise Office (RVO) • Spatial data (GIS) • Available spatial techno-economic models	• Insights building characteristics • Proxy heat demand per building type • Heat demand reduction strategies
Heat sources	• Availability and theoretical potential of regional and local sources (e.g. geothermal, residual heat, biomass, aquathermal) • Identification of restrictions • CO_2 emissions • System and end-user costs of heat supply options	• Local and regional assessment studies • Available spatial techno-economic models	• Identification and impacts of potential heat systems
Electricity and NG demand	• Average electricity use per building type • Average NG use per building type	• Data from the network operator Available spatial techno-economic models	• Electricity and NG use
Electricity and NG infrastructure	• Current capacity • Network constraints	• Data from the network operator	• Identification of constraints for LT- and MT heat systems
Heat demand and supply from existing DH networks	• Location and existing capacity DH network • Number of connections and heat demand • Existing heat sources and temperature DH network • Decarbonisation plans DH network • Potential capacity heat sources	• DH company data	• Current and expected future heat demand • Existing and future heat supply from DH network • Time planning and prioritisation of areas
Alignment with city infrastructure plans	• Age underground infrastructure • Timeline underground renovation (sewage-, NG-, electricity, DH- and water pipelines, fibre optic network) • Building renovation (e.g. municipal buildings) • Planned improvement plans (green spaces, parking) • Underground constraints	• Municipal data • Data from the network operator, water company and DH company	• Time planning and prioritisation of areas
Data from properties from housing associations and project developers	• Location properties of housing associations • Renovation/demolition and investments planned by housing associations and project developers	• Data from housing associations and project developers	• Time planning and prioritisation of areas
Alignment with citizens' initiatives	• Identification and plans of community energy initiatives • Potential heating technologies • Level of community support	• Local initiative gathered data	• Time planning and prioritisation of areas
Socio-economic characteristics neighbourhood	• Social- (e.g. unemployment levels, level of education), economic- (e.g. income) and environmental data (e.g. climate awareness) of city areas	• Dutch Statistical Bureau office CBS ('kerncijfers wijken en buurten') • Municipal data • Information from community-based initiatives	• Insights of socio-economic constraints and social support • Prioritisation of areas
Other	• Spatial impacts (available space ground and underground)	• Municipal data • Externally hired expertise	• Insights of spatial constraints of heat systems

studies. In the most extreme case (case study 19), the system selection is considered robust for only 0.7% of the dwellings. In the best option (case study 22), the robustness applies to only 20% of buildings. This outcome indicates that the most cost-effective technology is unknown in most city districts. However, when a lower spatial scale is applied (approximately three times lower) to cluster buildings with the same typology, the share of buildings with a robust outcome significantly increases (Fig. 5b).

4.2. Selected technical strategies

Table 3 presents the municipal technological choices until 2030. The implementation of DH as the primary strategy or in combination with individual systems (for areas with newer buildings) was chosen in 75% of the case studies. These are often large and medium-sized cities with a DH network in place. The existing DH network is expanded, or new networks are rolled out in areas with high demand and enough heat potential.

Heat availability for DH is unequally distributed among the case studies. While some municipalities indicated sufficient potential to fulfil their heat demand (e.g. case studies 3,9, 27), others indicated a deficiency (e.g. case studies 2, 20, 24, 25) and depended more on regional sources. Most small municipalities do not have the proximity of heat sources, the building typology and/or enough heat density to develop DH and choose individual heating systems combined with large-scale insulation programmes. Several interviewees from this group emphasised the lack of attention and best practices in applying individual technologies at a large scale, as DH networks are currently hogging the limelight at the national level.

Building refurbishment plays a central role in the strategic choices for the coming years. The refurbishment of buildings is seen as a no-regret measure that reduces emissions while preparing the buildings for implementing MT- and LT-heating systems. After understanding the numerous complexities (see Section 4.4), some case studies changed their initial strategy towards a step-by-step approach based on insulation instead of directly focusing on heat supply decarbonisation. Such a transition path also seems to align with citizens' preferences, who are more open to heat savings (i.e. lower energy bills) than adopting a new heating system in the short term. Large-scale insulation programmes will start in areas with a homogenous building typology and areas where the CO_2 reduction gain is most significant. Next, case studies planning to implement HTDH networks intend to shift gradually to MT and LT to minimise heat losses and increase the future flexibility for connecting different heat sources. Reducing the temperature from 90 °C to 55 °C is often sufficient to achieve adequate comfort levels for space heating.

The insulation degree must fit well with the heating alternative to avoid additional costs per unit of CO_2 reduced. Although energy

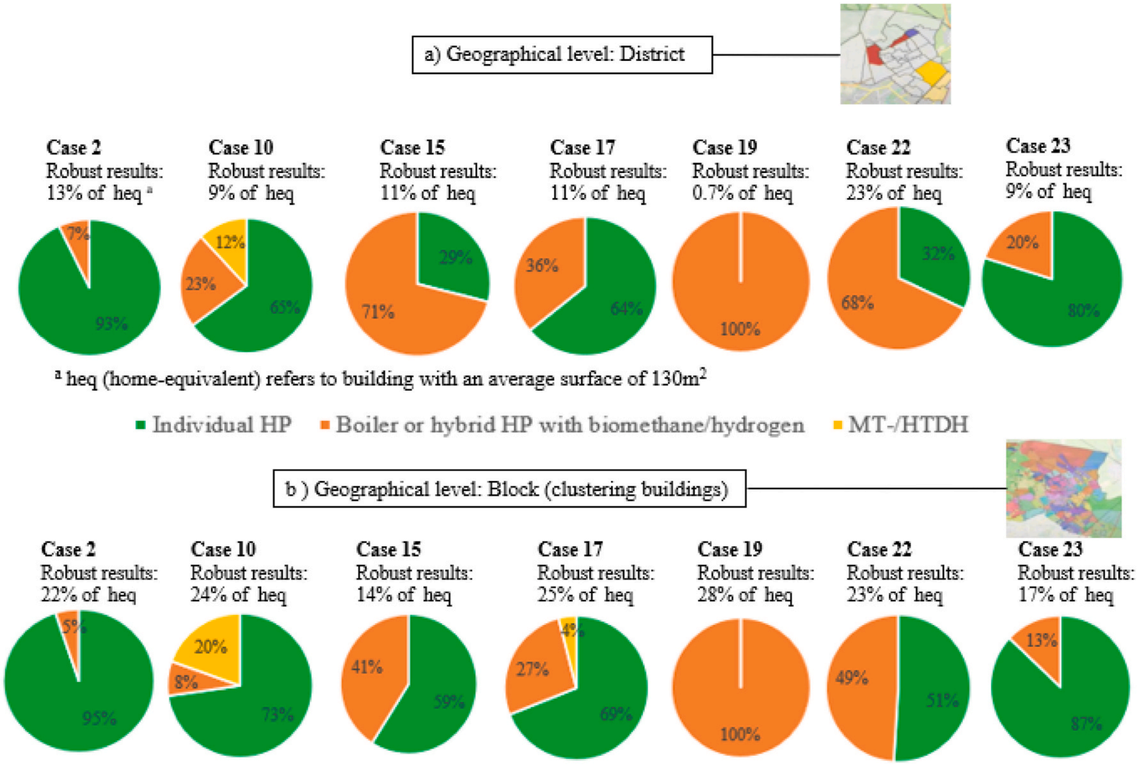

Fig. 5. Share of robust heating solutions at the district level (a) before clustering buildings and (b) after clustering buildings using the tool developed by Stedin (Stedin, 2021) for selected case studies. The selection was based on data availability. The pie charts give the technological mix in the share of home-equivalent considered robust. Selection of decarbonisation heat strategies up to 2030.

Table 3
Dominant strategies selected by the case studies to decarbonise heat in buildings until 2030. [a] Strategy often combines building insulation to reduce heat demand and, to a lesser extent, the implementation of HP in areas with new buildings; [b] = air-source HP or hybrid HP, often in combination with building insulation. This strategy can also include implementing small-scale LTDH systems in some areas but to a lesser extent. Red indicates large municipalities, yellow medium-sized, and blue small municipalities.

Selected strategy	# Case study	# Case study with an existing DH network in place		
		Large DH network (>150 TJ/year)	Small DH networks (<150 TJ/year)	None
Mainly DH networks [a]	1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14	1, 3, 4, 7, 8, 9, 10, 12	5 11 13	6 14
Mainly individual systems [b]	18, 19, 21, 22, 24, 25			18, 19, 21, 22, 24, 25
Combination DH and individual systems	2, 15, 16, 17, 23, 26, 27, 28		2, 17, 26, 27	15, 16, 23, 28
Unknown	20		20	

performance labels have been obligatory since 2008 when selling and renting houses, the interviewees reported that often such labels are unknown or outdated. Since Augustus 2021, these labels must include information on the building heat demand in kWh/m^2 (the so-called insulation standard). The standard provides the recommended heat demand per building period, serving as a reference for homeowners (Ministry of the Interior and Kingdom Relations, 2021).

Aquathermal-based systems are a prominent technology among the case studies due to the abundant water sources in the Netherlands (compared to residual industrial heat with more restricted availability). Most existing and ongoing aquathermal projects are small-scale, ranging from 1 to 1000 buildings (see Appendix B).

Most of the case studies are still investigating the potential of deep geothermal energy. One project has been implemented, and two projects are in preparation (see Appendix B). This source, offering high reliability, thermal efficiency and low operating cost, is seen as crucial to feed DH systems after 2030. The implementation of hydrogen and biogas by 2030 is being considered by only a few case studies as these technologies involve significant uncertainties (see Section 4.4.1). Three case studies investigate implementing a small-scale hydrogen plant produced by solar/wind to use the hydrogen locally. A neighbouring area of case study 5 plans to inject hydrogen in 2022 into the existing NG infrastructure. Case study 17, with a well-developed hydrogen infrastructure in an industrial area, assesses how hydrogen can serve as a heat source for parts of the city. The same municipality also has a good potential for biogas-heat, which currently feeds half the buildings.

Although most municipalities consider these two heat sources promising only after 2040, biogas and hydrogen can provide heat for buildings that are technically difficult to insulate (e.g. monumental buildings) and/or areas in the city centres where the limited underground space does not allow implementation of a DH network and where the existing NG infrastructure allows the transport of these gases.

4.3. Selected prioritised areas

Several criteria have been used to designate areas at the district level to start decarbonising heat systems by 2030. A general strategy is choosing areas with an existing project. Three aspects are commonly used drivers in the case studies:

- Starting with districts with early adopters, for instance, an energy cooperative bringing and stimulating the uptake of sustainable electricity, heat provision, or energy efficiency in their community. Bottom-up initiatives are great projects to learn from where some steps have been usually taken (e.g. feasibility studies, growing acceptance within the community for the required changes).
- Starting with areas where renovation or redevelopment plans are scheduled in the coming years, involving the city infrastructure (e.g. sewage- and water systems), the building level (e.g. housing associations properties) or a general improvement of the entire neighbourhood (e.g. greener areas, improved traffic safety, climate adaptation plans). Combining plans brings additional social benefits and may reduce nuisance for citizens and optimise costs. However, it appears to be complex in practice if agendas are not well aligned. It is often later in the realisation that it becomes clear whether binding infrastructure plans make sense. One barrier is the different technical and economic lifetimes of the various infrastructure. Difficult alignment has also been reported in agreements with partners and homeowners with various ambitions and agendas. Adopting a new heat system for rental properties of housing associations must fit their multi-year maintenance planning. For private owners, a logical moment appears when NG boilers need replacing, or a house is renovated, but this moment is different for each household. Another problem is the lack of regulation to coordinate the groundwork and reduce disruption during the construction phase.
- Implementing no-regret measures, including insulating buildings, implementing (hybrid) HP in well-insulated buildings, and prioritising areas where the identified heat alternative outstands as the most cost-effective. No-regret can also be the business-as-usual, as indicated by case study 17. Here, biogas is a crucial heat source with high expansion potential, which can be quickly materialised as it can be transported through the NG grid. The same applies to areas with existing DH networks, which have good potential for expansion.

Several case studies take a more pragmatic approach and select different projects purposefully. Experimenting with different technologies, bottom-up vs top-down approaches and with various building owners are beneficial learning experiences and a blueprint for future phases. Most investigated case studies start projects in two to five areas, a manageable number that allows municipalities to progress while learning.

4.4. Key challenges: from planning to implementation

Municipalities that have tried to translate their heat strategy into concrete implementation plans have faced several key challenges, which are categorized into five groups: i) technical uncertainties; ii) regulatory barriers; ii) economic barriers; iv) municipal capacity and v) information and instruments from the central government.

4.4.1. Technical uncertainties

Section 4.1 has illustrated that the technology selection is still uncertain in many city areas. The intrinsic technical immaturity and other critical issues are identified in this study regarding aquathermal energy, geothermal, hydrogen, air-source HP and biomass energy (Table 4).

The limited electricity grid capacity is a critical issue associated with systems relying on electricity. Seven interviewees reported grid restrictions have withheld the realisation of projects. Also, the large land requirements to generate sustainable electricity can be a problem in a highly populated and small country like the Netherlands. Fair land allocation is a discussion point in interregional dialogues and will be more crucial in the coming years. Similar discussions hold for large-scale potential heat sources like geothermal energy.

In recent years, there has been a changing perception regarding the sustainability of biomass as an alternative source for DH networks within the local government and in the Dutch society. However, excluding this source can make the heat transition even more complex as it represents the only option possible to decarbonise buildings in many situations.

Geothermal projects are complex projects involving unforeseen risks. Case study 5, having excellent potential for feeding the current DH network with geothermal energy, revealed that their plan was rejected after five years of discussions with the Mining Authority and the Ministry of Economic Affairs due to the risks of earthquakes. This process cost the municipality six million euros. Few other interviewees indicated that the city council does not support the technology due to the potential risks.

4.4.2. Regulatory barriers

There are currently no binding rules to force homeowners to remove their NG connection. Enforcement of housing associations' properties is easier because periodic agreements are made. The voluntary character has limited the momentum of ongoing projects (e.g. case studies 2 and 3) after significant participatory efforts to engage and motivate homeowners to adopt the new heat system.

New legislation, namely the Environmental Planning Act (Ministry of

Table 4
Identified issues and shortcomings regarding the technological choices considered.

Technology	Identified issues
Aquathermal	• Only feasible for buildings with minimum energy label B and near a water body • Temperature can be upgraded to 80 °C when a HT water-source, industrial HP is implemented. • Reinforcement electricity grid capacity required and additional land for renewable power production • Uncertain impact on water streams and biodiversity when using a large scale
Geothermal	• Only solution to decarbonise DH networks in many cases, but the real potential is still being investigated until 2025 (SCAN Aardwarmte, n.d.) • Uncertain risks (earthquakes, pollution) • Complex projects with many parties involved • Uncertain sectoral and regional distribution
Hydrogen	• Polarised views regarding applicability for heating buildings • Very low energy efficiency compared to, e.g. HP • High costs electrolysis • Reinforcement electricity grid capacity required and additional land for renewable power production • Adaption of the NG infrastructure required after a certain hydrogen share • Uncertain sectoral and regional distribution
Air-source HP	• Reinforcement electricity grid capacity required and additional land for renewable power production • Uncertain impacts with large-scale implementation on noise levels
Biomass and biogas	• Limited availability • Biomass is the only solution to decarbonise DH networks in many cases in a cost-effective manner, but polarised views regarding its sustainability among society and municipality

the Interior and Kingdom Relations, 2020) and Energy Act (Energiewet, 2020), is under development to regulate the period when the buildings must be connected to the sustainable heat supply. Several interviewees expressed the need for having the same legislation tackling electricity, heat and NG to avoid inconsistent rules. This process is under development, and there will be soon a new Energy Act. An inconsistency highlighted by case study 23 is the payment obligation (~800 €) for residents who voluntarily decided to shift to sustainable heating systems. This obligation has recently been removed.

The market of DH is currently regulated by the Heat Act 1.0, which focuses on consumer protection against excessive tariffs and couples heat prices with NG prices. The latter rule will be removed in the new Heat Act 2.0 (Toelichting, 2020), and a cost-based fee will be introduced. The new regulation, also under development, intends to set additional rules for market organisation, security of supply, CO_2 reductions and cost transparency. The Heat Act 2.0 assigns new responsibilities to municipalities like appointing DH zones, designating a DH company, and creating an inventory of customers who decide to join or opt-out from the DH network.

The main features of the legislative proposal and the issues raised by municipalities and other key parties during public consultation are described in Appendix C. The market organisation is a critical discussion point that causes municipalities and private DH parties to collide. Many case studies seek to take more public control in the management of the DH sector. Municipalities fear current commercial parties will cherry-pick, choosing the most profitable areas. Although the consultation round has led to a potential role for independent network operators and new public-private ownership models (see Appendix C), municipalities do not support the current proposal. Higher protection of public values is desired (Ministry of Economic Affairs and Climate, 2021).

4.4.3. *Economic barriers*

Compared to heating with NG, existing buildings' available low-carbon heat systems are generally not cost-efficient. There is unanimity among the interviewees that the lack of competitive heat alternatives and appropriate financing instruments are crucial problems in the Dutch heat transition. The issue contradicts the cost-neutrality principle settled by the Dutch Climate Agreement.

Most case studies emphasised that investments are not paid back by the energy savings, partly explained by the still-low NG price despite a recent tax increase. The financial gap is estimated to be half of the total costs. The PAW subsidies only cover half or less of the gap, as indicated by case study 8. Case studies 11 and 13 also complained that the lack of continuity of available subsidies is a problem for consumers and investors, generating uncertainty and high risks. Innovative solutions are being developed to solve the financial gap. Case studies 5 and 22 develop a financing instrument similar to an Energy Service Company concept. A service provider invests in the new heat system and makes a contract valid for 30 years, linked to the house and not the homeowner.

The lack of affordable solutions has been an eye-opener for several local authorities, provoking a turn in the initial strategies, e.g., from a complete decarbonisation strategy to a focus on the low-hanging fruit, i.e. a reduction of the heat demand. The costs can also be disproportionate compared to the value of houses, as expressed by case study 17:

> 'The costs of insulating an old house and implementing a sustainable heating system can easily reach 40,000 euros. In our city, houses in some districts cost just over 100,000 euros.'

Different cost figures are reported for the various technologies, which can be explained by the different house types and the components included in the calculations. Bringing a new DH network to existing buildings, primarily based on sustainable heat sources, is often unprofitable for DH (commercial) companies. According to the experiences done in the PAW pilots, costs per dwelling for DH can significantly range (10,000–40,000 €) and seems less economic-efficient than estimated due to the unexpected obstacles (e.g. high process costs, overloaded subsurface) (Arnoldussen et al., 2021). DH networks have difficulties competing with NG as the distribution tariffs for NG (and electricity) do not reflect the actual costs in an area since they are equated over the whole country (costs socialisation). This is not the case for DH.

The high risks, the little experience and the poor cost transparency explain the little costs figures known on the realisation of new DH networks. Some municipalities indicated that existing DH commercial companies are not always eager to share information about their revenue model and the costs incurred in the realisation. The new Heat Act will solve this by enforcing accountability and transparency requirements. Case study 13, advocating the public character of DH systems, calculated a 9000 € per house difference between public financial returns (2.2%) and private (6%). Together with case study 11, they started constructing a model to bring more transparency regarding cost division among the various actors and facilitate the decision-making.

More accurate cost figures can be found for HP systems because more experience is built with these technologies and involves lower risks and process costs than DH networks. The investment per household for an individual air-source HP ranged from 10,000 to 20,000 € excluding insulation costs (case study 2) until 30,000–40,000 € (case study 1) counting insulation.

In a few cases, the profitability of the alternative technologies has been proved positive because several conditions come together. An example is when properties in an area are scheduled for refurbishment, and the underground infrastructure needs replacement.

The lack of affordable alternative heat systems can explain the low support among homeowners, as reported by 40% of the case studies. Eight interviewees pointed out that if the financial and regulatory burden were solved, a critical burden remains; the changes required in the house environment (e.g. cleaning up the loft, bringing new ventilation and radiators) and social habits (e.g. operation of a new system). Few municipalities try to develop an all-included package including personal energy advice, minimum disruption and financing arrangements to reduce the hassle and make the change more attractive to homeowners.

4.4.4. *Municipal capacity*

Developing a heat strategy and preparing the first implementation plans requires new technical, financial and legal knowledge from municipalities. This has been managed with limited municipal resources and capacity. Two-thirds of the case studies recognised that more financing is needed to increase their limited resources and achieve the goal to decarbonise 1.5 million homes in 2030. One-third stated that their in-house expertise in the heat transition is insufficient.

The problem has led to a strong dependency on external expertise during heat planning. In the majority of the case studies, a consultancy or temporary staff (~1 year for 2–3 days a week) was hired to support the municipality in the whole trajectory or at specific phases, especially during the techno-economic assessment. The exception is case study 10, which created an internal modelling team to make its modelling runs with Vesta MAIS while refining the input data in the coming years. Few municipalities could find the right expertise within the municipal team or the partners in their working group, depending less on consultant services. Three of the interviewed small municipalities have established a collaboration with nearby municipalities to learn from each other and save costs (e.g. hiring external expertise and implementing specific steps).

Although municipalities received financial support from the central government to elaborate the heat strategy plan, the financial means to fulfil the given responsibilities are perceived as inadequate. Numerous interviewees pointed out that this problem will become more prominent when implementation plans start because new municipal tasks are assigned to them as proposed by the Heat Act 2.0 (Section 4.4.2).

Fig. 6 presents the case studies' reported number of municipal officials in full-time equivalent (FTE). While some municipalities have a dedicated team responsible for heat, employees are often involved in all energy- and sustainability-related projects. Small municipalities indicated that up to a few years ago, only one person working part-time was dedicated to all themes (e.g. energy, heat, mobility, circularity, climate adaptation). The absolute number of FTE in the municipal team among large municipalities (Fig. 6 left) differs significantly, while the numbers from medium and small municipalities are comparatively constant. Examining the relative values per number of inhabitants (Fig. 6 right), the differences among large municipalities are minimised, while these become greater for small municipalities**.** Although the relative values offer a better comparison among the municipalities, the organisation required to draft the municipal strategy during heat planning, especially for those who just started the process, might not depend on the number of inhabitants but the process's complexity. Staff shifts are frequent in the municipal teams, but the numbers reported in Fig. 6 do not consider the differences in workers' permanency.

4.4.5. *Information and instruments from the central government*

The interviewees generally appreciated the information and instruments offered by the central government to tackle the heat transition (e.g. the national techno-economic model Vesta MAIS, the Expertise Heat Center and the PAW program). However, they do not always align with the local needs. Municipalities opt to develop their own instruments or search for external advice when this happens.

Few shortcomings are identified in the application of Vesta MAIS. First, the model focuses on technologies that are still unavailable on a large scale or entail significant uncertainties (e.g. hydrogen, biogas). Second, its complexity of use for municipalities with no programming skills leads to dependency on external models and expertise to produce and interpret the outputs. Third, the model only reports system costs and not end-user costs. The latter appears crucial in communicating with the building owners and the city council, which has moved several municipalities to make the analysis themselves. Tigchelaar et al. (2021) recently developed a model that assesses the costs for five different house types with various refurbishment levels and energy behaviours.

Nine case studies were awarded by the PWA subsidy scheme (Table 1) and received 4 to 8 million € each. The national pilots supported by the scheme have brought valuable national and local lessons, as investigated by Arnoldussen et al. (2021) and Dignum et al. (2021). However, there has been hardly any progress made in realising projects. Only one of the case studies accomplished the initial goal three years after the program's start. However, this example cannot be used as a blueprint for other projects. Before the project started, most dwellings in the case study were already connected to a DH network. The subsidy was only used to bring new insulation, solar panels and induction for cooking. Although the poor realisation might be normal in an experimentation phase, the current pilots test simultaneously many facets and have encountered unexpected problems to disconnect buildings from the NG grid.

The PAW program does not always target business-as-usual, ongoing projects that are ready for realisation. This contradicts the need of municipalities (case studies 2, 3 and 6) for financial support to achieve realisation. Next, case studies 7 and 16 signalled a lack of well-supported argumentation from the central government for not choosing their project. Not receiving the subsidy has hampered the progress made in some situations and has been perceived as poor recognition of the municipal efforts. The projects needed this financial assistance to take further steps and keep the momentum in the working group.

Last, there is a desire for a clear and strong message from the central government regarding two aspects. First, to be clear about the limitations and feasibility of some technologies, such as hydrogen and biomass, whose applicability and future to decarbonise heat supply in buildings raise opposing views and contradictions. Second, to accentuate the urgency of the heat transition in the short term, which can stimulate a shared understanding and increase support among the Dutch society. Others, contrastingly, perceived that the blast of information in the news in recent times regarding the heat transition is tiresome and creates scepticism among the population. They suggest the national message should be enriched and shifted towards other benefits, such as more comfortable and healthy houses with lower energy bills.

5. Discussion

This section reflects on the main findings relevant to the identified research gap, comparing the results with existing literature. Next, research limitations and suggestions for further investigation are presented.

5.1. *Addressing the knowledge gap*

What knowledge regarding the heat planning for regions in the learning and preparatory phase of the heat transition does this research bring? The study exemplified the complexity and premature conditions experienced by municipalities to translate a national goal into concrete local plans and realised projects. Our notion is that the central government did not fully foresee the difficulties and impact of implementing its ambition. Most local governments, large, small and medium-size, are still in the learning phase, trying to find the right strategy while facing numerous uncertainties and barriers. Similar experiences are observed in historical heat transitions in the Netherlands, UK and Denmark, which did not start as carefully planned projects and where these qualities emerged over time (Bertelsen et al., 2021).

We learned from past transitions that effective policy and

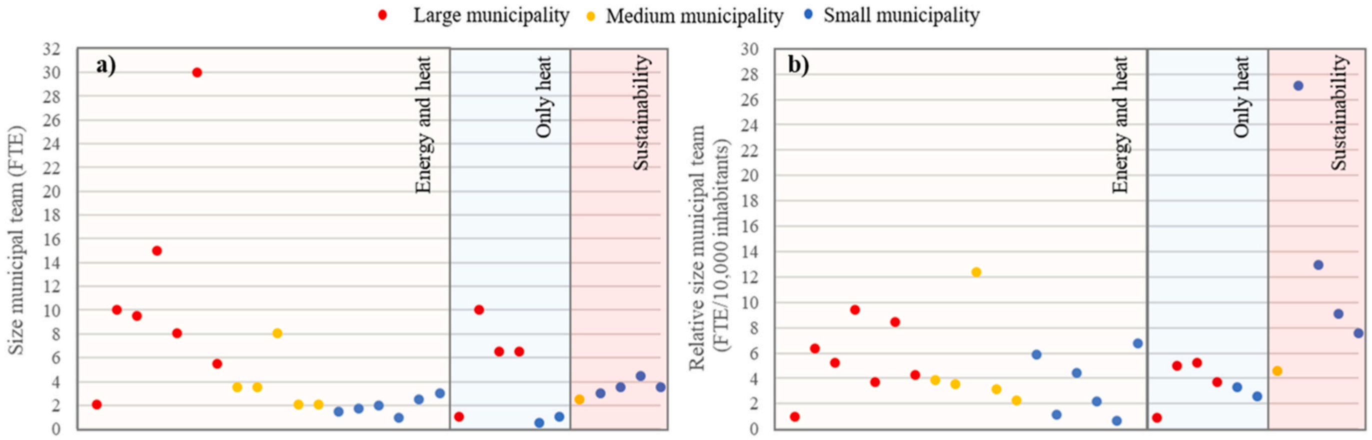

Fig. 6. Size of the municipal team in absolute values (a) and relative to the number of inhabitants (b) working for energy-, heat- and sustainable projects in the case studies.

governance frameworks were critical in enabling actors to plan, invest, and implement new systems (Bertelsen et al., 2021). In this context, our study identifies important barriers. Some of the lock-in effects anticipated in earlier studies of the Dutch heat transition, namely the financial bottlenecks and lack of social support (Schilder and van der Stark, 2020; Scholte et al., 2020; Tigchelaar et al., 2019), the regulatory burdens (Tigchelaar et al., 2019), and the lack of expertise in municipal teams (Diran and van Veenstra, 2020; Studiegroep Interbestuurlijke en Financiële Verhouding, 2020) are confirmed and further assessed in this research based on a broader analysis. Additionally, this study sheds new light on other lock-in effects (i.e. technical barriers and shortcomings of available national information and instruments) and the municipal approach during heat mapping, technology selection, and prioritised areas. This complex and interactive process involves wide-ranging techno-economic, social and organisational decision-making. The study also identifies a preference to take more public control in DH networks to safeguard public values and move away from just the most profitable strategies. Future regulation may enforce municipal positions and stimulate the growth of the initial DH market, as has historically occurred in Sweden and Denmark.

Interestingly, comparable findings are observed in other countries starting a heat transition, such as the UK, where local governments are reconsidering their ownership in DH networks (Britton, 2018) and the limited municipal staffing levels, financial resources, and regulatory uncertainties restricted the realisation of municipal climate ambitions (Bush et al., 2016; Hawkey et al., 2013). Although the UK deals with an analogous contextual situation as in the Netherlands in terms of heating systems and level of ambitions to phase out gas boilers in buildings (Climate Change Committee, 2022), their approach is more centralized without an overall framework for the role for municipalities in heat planning (Tingey and Webb, 2020). This and other institutional conditions under which the actors operate (e.g. regulation, access to financial resources and municipal capacity) influence the applicability of our findings to other contexts.

The problem of ensuring an effective decentralization by backing up municipalities with access to information, clear guidelines and capacity from the central government is also observed in front-runner countries. Danish municipalities, for example, working towards modernising their heat systems, experience similar institutional constraints (Sperling et al., 2011). Generally, the problem of local dependency on national umbrellas that provide the necessary incentives, resources and regulatory frameworks for cities to undertake climate action is a recognised problem across regions and low-carbon actions (Fenton et al., 2015; Fuhr et al., 2018; Hoppe and van Bueren, 2015). Therefore, the local dependency on national support seems not only a problem in the early phase of the heat transition but an issue that requires careful monitoring and support from national climate strategies in all phases.

Our study has shown that data provision, available at the national level and from municipal partners, has supported the local governments in taking the first steps. The interviews revealed the need for data standardisation and open-source data, especially for the available techno-economic models. Public officials do not have established practice for heat modelling, so they rely heavily on external expertise to apply the national methodology Vesta MAIS and other non-open-source models (which are inaccessible for independent review). The problem may impede the adequate interpretation of the results and future adjustments of the models to integrate local and more refined data. Similar findings on using existing models by local decision-makers are found in the Netherlands (Diran and van Veenstra, 2020; Henrich et al., 2021) and other European contexts (Ben Amer et al., 2020; Cowell and Webb, 2021; Delmastro and Gargiulo, 2020; Johannsen et al., 2021).

As the technical systems are comparable in terms of cost-efficiency for many municipal areas, other arguments (e.g. comfort, emissions reduction, autonomy) might be decisive. Assessing wide-ranging criteria (e.g. social and environmental) beyond techno-economic criteria would also better reflect the broader motivations of municipalities (Bush and Bale, 2014). Our research shows that DH networks of various temperatures and sizes will coexist with individual heating systems. Individual systems and small LTDH networks seem critical for smaller and less populated cities. However, several financial, market and technical barriers must be mitigated before the new heating systems become widespread. Social acceptability is also a determining factor. For example, whether biomass will be a temporary resource disappearing from the heating sector is unclear. Similar discussions hold in other countries (Harrestrup and Svendsen, 2014), whereas biomass seems to be a widely accepted transition fuel in other contexts (Kontu et al., 2015; Mazhar et al., 2018). The numerous uncertainties make it challenging to look beyond five years ahead in municipal plans. It will require an adaptation of their strategy once uncertainties are minimised.

Tackling poorly insulated buildings is seen as a cost-effective pathway. A lower energy bill and healthy and more comfortable houses bring less opposition and debate among homeowners than directly switching to alternatives for cheap NG. This approach is also suggested for countries with a similar situation – e.g. the UK (Broad et al., 2020) - and aligns well with the European strategy, pursuing doubling the energy renovation rates in the next ten years (European Commission, 2020). However, large-scale deep retrofitting requires time, is labour intensive and can be costly as insulation material and labour costs have increased significantly in the past years (van Rooij and Heins-Wundelre, 2021).

5.2. Limitations and suggestions for further research

Several limitations of this study need to be considered. Although the interviews' results have been compared to the available municipal official documents and other reports to improve data quality, this comparison relied on data availability which differs among the municipalities. Paired interviews with public officials would increase data representativeness. Nevertheless, information such as data used for heat mapping and the technological- and area selection can be considered factual and less biased than, for instance, the challenges pinpointed during the interviews. Yet, the identified challenges align well with existing studies.

The current analysis only looks at the current experimentation phase involving fast dynamics. Repeating the analysis in a year (with different contextual factors) may lead to other outcomes. The speed at which the transition occurred in other energy systems (e.g. solar energy and electric vehicles) exemplifies the importance of the time dimension. Thus, further research is also needed to understand how the lessons from the current experimentation phase - aiming to decarbonise only 20% of the buildings in 2030 - can be upscaled and translated to millions of homes and into a different socio-technical context. These are crucial aspects of strategic policy-making and will enable better local and regional planning in the medium- and long term.

The themes investigated may be too limited and preclude understanding other crucial elements in the local strategy. One example is how heat planning is integrated into urban development, providing a broader overview of comprehensive solutions, optimising costs and bringing additional benefits. Another example is understanding the trade-offs between supply and demand-side interventions over the long term, as energy efficiency strategies in buildings can influence the cost-efficiency of heat supply systems (Harrestrup and Svendsen, 2014).

Last, a deep analysis of how municipalities engage with their communities and coordinate efforts with key stakeholders (e.g. energy companies, network operators, housing associations and local businesses) is needed to understand how these groups support the municipal decisions. The successful implementation of large-scale heating infrastructures in the past (e.g. NG in the Netherlands and DH in Denmark) resulted from a great collaboration between governments, consumers and private parties (Bertelsen et al., 2021; Krog, 2019). Expanding the interviews with other key stakeholder groups may also bring a richer interpretation of the challenges of the heat transition.

6. Conclusion and policy implications

6.1. Conclusion

Planning and implementing low-carbon heat systems in buildings are new responsibilities for Dutch municipalities. The study portrays the approach and complexities Dutch local governments face as primary actors during this process.

An overarching lesson is that effective local governance of the heat transition requires the timely establishment of supportive mechanisms. The lack of binding policies to terminate the NG supply, poor affordability of heat alternatives and insufficient financial support has hindered local efforts to accomplish this goal. Ongoing legislative changes will enable the steering possibilities for local governments and the uptake of DH networks. However, municipalities are dissatisfied with the regulatory proposal and seek a better public positioning within the privately-oriented DH market.

Selecting low-carbon technologies and prioritising areas is an interactive process, requiring techno-economic, social, environmental, and organisational criteria. The research revealed data standardisation opportunities and a desire for more locally applicable instruments. The national efforts in data provision appear inadequate as municipalities strongly rely on external expertise to grasp the required knowledge.

DH networks at various temperature levels, sizes and fed by different sources are popular strategies among large and medium municipalities with high heat demand areas. In contrast, small municipalities opt for individual heating systems or small-scale LTDH networks. For many municipal areas, the various technical systems are comparable in terms of cost-efficiency; therefore, other arguments (e.g. comfort, emissions reduction, autonomy) might be decisive. However, heating alternatives are unknown to society, rely heavily on a constrained electricity grid, and some face low public support. A clear and strong message from the central government is needed to clarify the limitations and feasibility of some technologies and increase societal support.

Building refurbishment is seen as a cost-efficient transitional measure. It gives the time to prepare the regulatory framework, conceive innovative financing instruments, progressively minimise the technical uncertainties and increase the know-how among the municipalities. A lower energy bill, healthier and more comfortable houses are also socially more widely supported than switching to heat alternatives that are still unknown to the consumer and do not deliver immediate benefits.

6.2. Policy implications

Based on the abovementioned conclusions, this article brings the following policy implications for national authorities (NA) and local authorities (LA).

First, setting too ambitious national targets is not necessarily a good starting point if no binding instruments are provided to assist LA in their leading role in the local heat transition. The timely establishment of adequate and consistent regulation is critical in the starting phase.

Second, clarity is needed on the potential financial mechanisms to spread costs along the chain and ultimately close the current financial gap to switch to low-carbon heat systems. NA can clarify which allocation mechanisms (e.g. taxation, public capital, guarantees, loans, an increase of building value) will play a role in the short- and long term for various situations and income profiles. Certainty in these fronts can increase investment security. Policy structures are also needed in which local governments can both experiment and support ongoing projects that need financing to achieve realisation. The latter can bring confidence, progress and commitment to LA and stimulate market- and societal uptake.

Third, increasing municipal competencies and capacity must be an ongoing multi-governance effort for effective decentralised heat planning. Hiring external advice, primarily when the municipality cannot assess the received expertise, is not a structural solution in a long-term transition preventing the development of local knowledge. It also puts an extra burden on the limited municipal financial budget. NA must equip municipalities regularly with adequate capacity and expertise. Regional governments may support and coordinate municipal efforts while convening concrete local needs to higher government levels. LA must focus on increasing long-run skills, minimising staff shifts and determining which expertise is indispensable and can be sporadically externalised. Public-private partnerships can offer LA access to expertise and capacity while bringing capital and risk mitigation.

Last, designing flexible planning local strategies, like starting with heat savings, is recommended in the presence of numerous uncertainties. LA must find a balance between written plans and execution. The balance should also be found between the time spent on each step of the planning stage (e.g. the techno-economic assessment and other social, environmental and organisational objectives). Simple tools that assess potential strategies from these different angles may assist the local decision-making. Open-source data and consistent guidelines on employing various techno-economic models can bring a uniform reference and more validity to the heat mapping exercises. Finally, NA can also bring clear messages to society regarding the short- and long-term technology's feasibility and the urgency of the heat transition, which can strengthen the position of LA in the communication and engagement with their communities.

CRediT authorship contribution statement

Sara Herreras Martínez: Conceptualization, Data curation, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Robert Harmsen:** Funding acquisition, Conceptualization, Writing – review & editing. **Marijke Menkveld:** Funding acquisition, Conceptualization, Writing – review & editing. **André Faaij:** Funding acquisition, Conceptualization, Writing – review & editing. **Gert Jan Kramer:** Funding acquisition, Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2022.113169.

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