UNIVERSITY OF TWENTE.

Energy Transition in Urban Netherlands through Heat Pumps: A Fuzzy Cognitive Map-Based Approach

Case study of Leeuwarden

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Abstract

This thesis examines the application of the Technology Acceptance Model (TAM) in a case study in the urban Netherlands. It studies the transition towards heat pumps in the Dutch built environment, aligning with the country's goals of energy transition, and phasing out of natural gas. Heating in buildings plays a substantial role in contributing to greenhouse gas (GHG) emissions, and to tackle this challenge, a rising demand for energy transitions has emerged. To achieve its climate neutral goals, the Netherlands has set ambitious targets, including the phasing out of natural gas in the residential sector and heat pumps have emerged as a promising solution to replace natural gas in residential heating systems. Accordingly, the present research through an experimental analysis approach, aims to identify the factors that contribute the broader technology acceptance of heat pumps and predict the future possibility through techno-economic changes in the system's dynamics. To this end, the study identifies relevant determinants using the TAM and examines hypothetical scenarios to recognize potential factors that could enhance residents' attitudes. The research begins with a public survey conducted in the city of Leeuwarden, representing urban Netherlands, to gather comprehensive understanding of residents' attitudes, concerns, and experiences regarding heat pumps. In the next step, expert opinions were captured to evaluate the interlinkages and impacts between different concepts related to heat pump adoption, covering social, environmental, technological, and economic aspects. The data obtained from the surveys are then used as input for fuzzy cognitive mapping (FCM) to qualitatively compare concepts in the system. Then, a scenario-based analysis is performed using the derived FCM causalities to assess the effects of alternative scenarios on heat pump adoption and the transition away from natural gas. Four scenarios are designed and tested to explore potential outcomes of different policy options, measures, and actions aligned with the Netherlands' energy transition goals. Furthermore, based on the findings and analysis, recommendations have also been proposed which should be incorporated to improve the wider acceptance of heat pumps.

Keywords: Heat pump, Energy transition, Public attitudes, Fuzzy Cognitive Mapping (FCM), Technology Acceptance Model (TAM), Natural gas, Urban (residential) areas

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Acronyms

GHG: greenhouse gas emissions

NL: Netherlands

CV: centrale verwarming (central heating)

TAM: technology acceptance model

FCM: fuzzy cognitive map

HVAC: heating, ventilation, and air conditioning

1. Introduction

1.1. Background

The need for acceleration in reducing global environmental impacts of greenhouse gas (GHG) emissions is felt today more than ever and direct emissions from heating in buildings make a significant contribution to that. In 2021 the direct emissions to space and water heating in buildings reached an all-time high of 2.5 Gt (IEA, 2022d). To address this issue, there is a growing need for energy transitions that can reduce the reliance on fossil fuels for heating.

Most of the energy used to heat buildings comes from fossil fuels like natural gas and oil (see Figure 1), and since these fuels contribute to the overall level of GHG emissions, it makes it more pressing for energy and heat transitions.

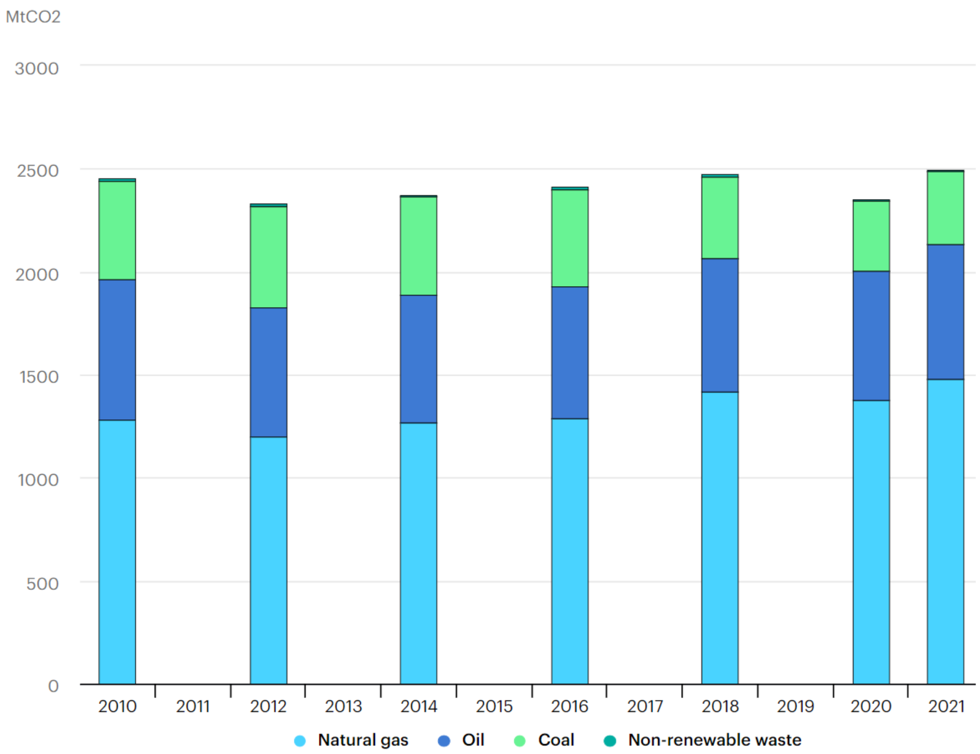

Figure 1: Direct CO2 emissions from buildings-related heating by fuel (IEA, 2022d)

The Netherlands has set ambitious targets in this regard. The country has committed to reducing its GHG emissions by at least 49% by 2030 compared to 1990 levels, and to achieve a 95% reduction by 2050 to combat climate change (Ministry of Economic Affairs and Climate Policy, 2022). These targets are in line with the goals of the Paris Agreement on climate change, which seeks to limit global temperature to below 2 °C above pre-industrial levels (UNFCCC, 2018).

One of the main plans in the Netherlands to achieve these targets is by phasing out the use of natural gas in residential sector and replacing it with more sustainable alternatives. The Netherlands has some policies and measures to support this transition that is also part of the commitment to the COP26 targets of mitigation and adaptation. For instance, it has planned not to connect new buildings to the natural gas grid, introduced in 2018 as a part of the government's efforts to encourage the usage of renewable energy in buildings. About 90% of buildings in the Netherlands, are still using natural gas or oil for their heating that is mainly used for space and water heating (CBS, 2022a). To achieve the climate objectives, it is necessary to adopt alternative heating technologies that run on sustainable energy sources. Some of the new alternatives that can reduce the reliance on natural gas for heating are heat pumps, geothermal energy, and district heating. These technologies offer efficient and sustainable ways to heat buildings and lower the reliance on natural gas to meet the heat transition goal. In this thesis, the focus shifts to exploring heat pumps as a key alternative for reducing reliance on natural gas for heating.

1.1.1. Heat pumps

This subsection provides an overview of what are heat pumps, various types of them available on the market, state-of-art advancements, technology readiness, and attempts to clarify in which way heat pumps can play role to reach climate goals.

To start with a definition to heat pumps, they are a technological approach in the heating sector which use electricity to extract heat from a source that could be air, water, or geothermal energy and after amplifying it, and transfer it into a building using a refrigeration cycle. Main components of a heat pump are evaporator, compressor, condenser, expansion valve, and coolant. To explain how a heat pump operates: the heat is absorbed by the coolant from the outdoor air through the evaporator, next its temperature rises through compression in the compressor, after that, heat is transferred from the coolant to the space through condenser coils, and then, it goes through the expansion valve to cool down and repeat the cycle (IEA, 2022c). Figure 2 shows how a heat pump extracts the heat from the outside environment that is absorbed by the refrigerant and transfers it by a pump to inside of the home.

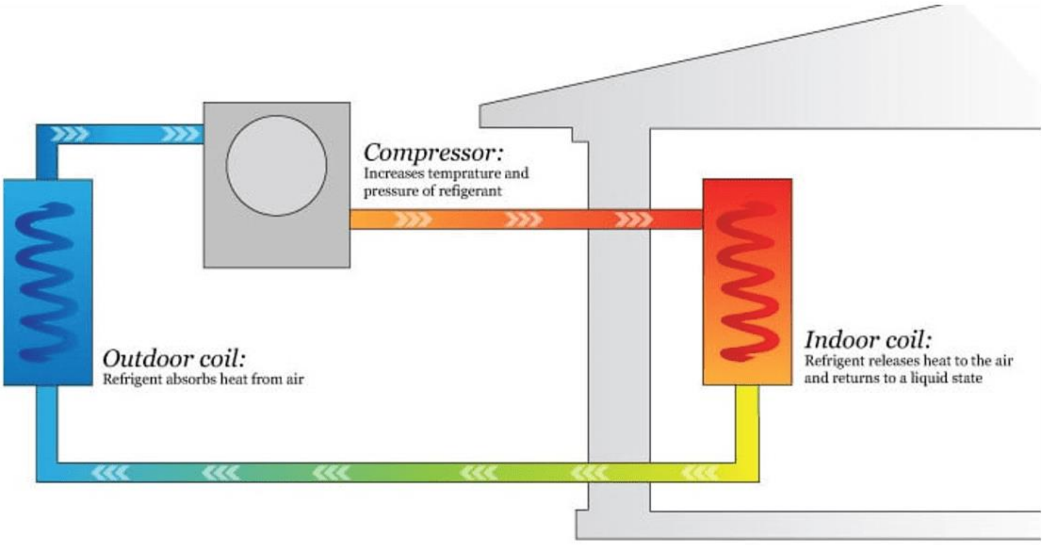

Figure 2: Main components of heat pump and process diagram

There are various types of heat pumps on the market based on the source of heat, including air source, water source, and geothermal source, and the refrigerant they use in the cycle.

Figure 3: Outdoor unit of an electric heat pump

They could also be classified based on the energy type they use to be run. Figure 3 presents a picture of the outdoor unit of a typical air source heat pump. Accordingly, heat pumps could be fully electric or use a combination of electricity and fuel, such as natural gas. If the heat pump is of the latter case, it is so-called hybrid heat pump. Figure 4 illustrates a schematic of the conventional gas heating system, which is currently the dominant heating system for homes in the Netherlands, and two alternatives of fully electric and hybrid heat pumps.

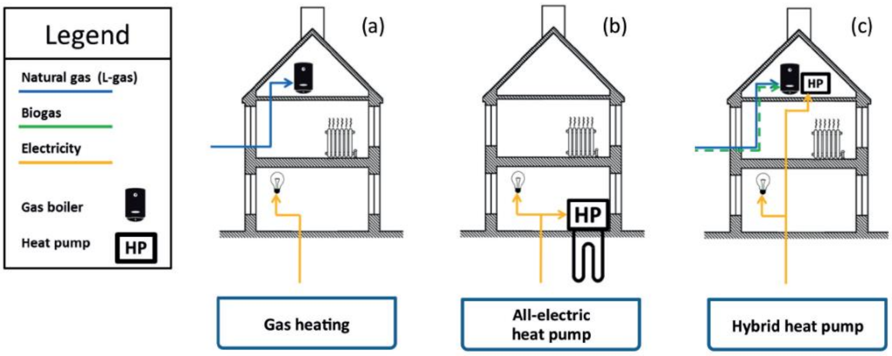

Figure 4: Schematic of residential heating systems: (A) Gas-based heating, (B) Fully electric heat pump and (C) Hybrid heat pump (Klip, 2017)

If the heat pump is all-electric, it receives the needed power to operate, fully from electricity. While electric heaters can directly convert electricity into heat, the efficiency of this process can be significantly higher by utilizing heat pumps (Carroll et al., 2020).

1.2. Problem statement

As phasing out the natural gas from buildings heating with the goal to reduce the emission of CO2 becomes more decisive, it calls for the adoption of technologies which use more renewable energy sources. To this end, electrical heat pumps are seen as a solution to phase out the use of natural gas and subsequently, reduce emissions. As said, government policy is that heat pumps should be the norm in the Netherlands (Netherlands Enterprise Agency, 2022b). The government is allocating subsidies to help owners, which covers up to about 30% of the cost to change. The technology of heat pumps is almost mature, and still there is a great deal of activity in terms of advancements in terms of efficiency and performance.

However, increasing the use of heat pumps in residential settings is not only reliant on the performance and technological factors of a heat pump. But the extent to which it is accepted and adopted by households and what is the attitude of households -as the end-users- about using heat pumps as the heating device at their homes is another aspect of the matter that must be considered. Ownership of the building could be another issue where tenants may face challenges installing a heat pump due to the need for landlord approval. Scientific literature on heat pumps also confirms the need to further work to understand the residential uptake and household behavior towards heat pump adoption (Lin et al., 2021).

According to the International Energy Agency (IEA) there are key technology challenges to be solved to reach long-term energy transition targets. (IEA, 2019). As indicated above, heat pumps are one of the innovations in the building sector that require more research, development, and demonstration; and one of the key challenges to be addressed is raising heat pump attractiveness. High upfront prices of heat pumps and lack of adaptability are some of the known issues (IEA, 2022a).

On the other hand, due to the concentration of economic activities, transportation, and industrial facilities, urban areas often become emission hotspots. Urban areas in the Netherlands have high population densities, resulting in concentrated energy demands and as a result accounting for a substantial portion of the country's total energy consumption. According to the World Bank's development indicators, the Netherlands' urban population (as a percentage of the country's total population) was 92.89% in 2022 (THE WORLD BANK, 2023). This makes urban areas in the Netherlands more crucial to address in reducing greenhouse gas emissions and promoting sustainable energy use, such as heat pumps.

1.3. Research objectives

Objectives of this research are to analyze the factors that contribute to heat pump adoption at household level, their attitudes towards the topic, and suggesting possible solutions to enhancing attitudes towards adoption of heat pumps by domestic users in the Netherlands. In addition, this research aims to assist policymakers by using the Technology Acceptance Model to create hypothetical (what-if) scenarios for heat pump adoption and leveraging insights into social attitudes towards heat pumps.

1.4. Research questions

Main question

How can technology acceptance accelerate the adoption of heat pump systems in urban NL?

Sub-questions

To answer this question, the following sub-questions are posed:

1) What are the key factors that influence the decision of urban households to install a heat pump system in residential buildings?
2) Which techno-economic changes can enhance the residents’ attitude towards heat pump adoption?

2. Literature Review

This section encompasses several key areas. First, it will explore the current state of residential heating in the Netherlands. Following that, an exploratory overview of heat pumps will be provided. Subsequently, the theoretical framework of the TAM will be introduced, and finally, the FCM technique will be presented.

The adoption of sustainable heating systems for residential areas may encounter challenges in terms of acceptance by society. Yet studies that have incorporated social concerns and attitudes into modeling techniques are limited. A survey research in Beijing assessed the possibility of public acceptance towards low temperature air source heat pump technology and explored the people's willingness to adopt and pay for it as a new electric heating system (Jingchao et al., 2018). One study evaluated interviews and observations conducted with users and installers who participated in the initial trial of SHHP (Smart Home Heating Project) in the UK (Parrish et al., 2021). Energy transition processes in the multi-level perspective of niche development, regime development, and the involvement of local people were investigated in a case study in the Dutch island of Ameland (van Dam & Van der Windt, 2022).

2.1. Current residential heating installations in the Netherlands

Natural gas is the primary energy carrier in the Netherlands and many buildings rely on it for their heating needs. So, gas boilers are by far the most used systems to heat houses in the country. As shown in Figure 5, by the end of 2021, 82.2% of homes use individual CV, i.e., central heating (Dutch: centrale verwarming). Individual CV here stands for a natural gas fired boiler. In contrast, about 1.4% of homes use hybrid or fully electric heat pumps (CBS, 2022a).

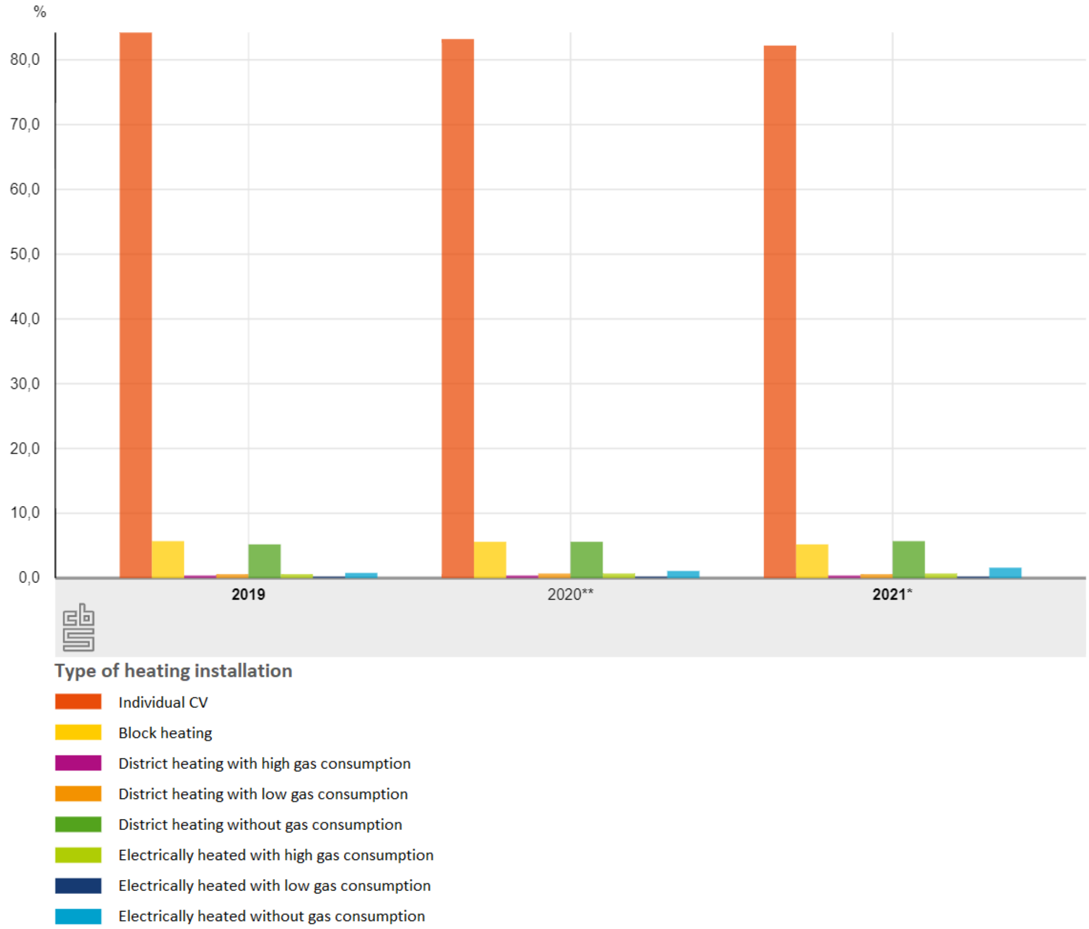

Figure 5: Main heating installations in the Netherlands (CBS, 2022a)

As said, alternatives for residential heating towards reducing reliance on natural gas are varied. Latterly, there has been a growing attention into heat pumps as a solution in the short to medium term (Delft, 2022). According to the Netherlands Enterprise Agency (2022b), when replacing a boiler, hybrid heat pumps would be mandatory for households in the Netherlands from 2026. This basically means that using hybrid heat pumps would be the standard for heating the homes and residents must install a hybrid heat pump when their gas boilers need to be replaced. And, if the hybrid types are not applicable for some homes, a fully electric heat pump would be another possible option.

According to data from national statistics agency CBS, a total of 1.3 million heat pumps are now in use that about 939000 of this number are installed in homes (CBS, 2022b). This represents around 11% of the total housing stock in the country (CBS, 2023). The Dutch association of national-regional electricity and gas network operators, has a plan supported by the government, to install up to 2 million hybrid heat pumps in the Netherlands by 2030, with a goal of installing at least 100,000 per year starting in 2024 (Netbeheer Nederland, 2021).

2.2. Exploratory overview of heat pumps

Heat pumps may vary in design, application, and heat source they use. They could also be all-electric or hybrid (using a mix of electrical power and natural gas) in terms of the energy they use to function. But generally, all of them consist of several parts including evaporator, condenser, compressor, expansion valve, and refrigerant that is also called coolant. The other components may vary based on the application and design of a heat pump.

Electric heat pumps utilize electricity to function and extract heat from the surroundings outside of the system which is called heat source. Accordingly, all-electric heat pumps can be divided into three main types of air source heat pump (ASHP), water source heat pump (WSHP), and ground source heat pump (GSHP) (Chengmin et al., 2012; Kegel et al., 2012; Ma et al., 2020). These heat pumps do not use gas to run and the heat that is absorbed and transferred to the building's heating system could provide space and water heating.

Among the mentioned types, ASHPs are one of the most prevalent types of heat pumps due to their rather ease of use, low infrastructure requirements, and their positive environmental impact (Hu et al., 2019; Y. Zhang et al., 2017). While ground source and water source heat pumps can perform with higher efficiency, because of higher initial costs and the specific skills and techniques required for installation, they account for a relatively small percentage of global sales. Worldwide, almost 85% of all heat pumps sold for buildings are air-source, as they require the least effort to be installed (IEA, 2022b).

The two types of ASHPs are air-to-air and air-to-water, i.e., the heat is extracted from the ambient air, and it could be transferred to either air or water (Staffell et al., 2012). The ability to deliver both heating and cooling makes air-to-air heat pumps advantageous since it makes them more suitable for providing temperature control throughout the year (Lun & Tung, 2019). Yet, since most of the Dutch residential buildings typically use boilers and water-circulated central heating systems (CBS, 2022a), it may make air-to-water heat pumps a more fitting technology as they can integrate with the existing infrastructure.

2.3. Environmental aspects

Heat pumps are becoming one the most popular technological approaches as a short to medium term solution towards reducing energy use and emissions. They can play a crucial role in reducing energy usage and CO_2 emissions in residential sector and support the shift towards low-carbon energy sources (Allouhi, 2022; Borge-Diez et al., 2022). There is a wide range of studies showing that heat pumps could reduce carbon emissions, lower energy consumption, and improve the overall energy efficiency (IEA, 2022e; OAK RIDGE National Laboratory, 2017). The utilization of heat pump technology on a large scale also has the potential to enhance air quality and consequently enhance public health. For example, Carella & D'Orazio (2021) explored the role of heat pumps for better urban air quality in Rome, Italy. They analyzed the concentrations of pollutants in the air, comparing the existing gas boilers with air/ water heat pumps. The results of this study showed that the implementation of heat pumps at the urban level can lead to long-term reduction of air pollution by significantly decreasing emissions (12% to 56%) in the city.

Furthermore, the heating technology industry is beginning to adopt natural refrigerants such as propane and isobutane for heat pump technology which are synthetically beneficial alternatives (Alonso et al., 2022; Bahman et al., 2022). It is a while now that natural refrigerants are considered the most favorable and eco-friendly refrigerants, serving as the ideal solution to ozone layer depletion and global warming (Bouzghiba & Géczi, 2022; ELBİR et al., 2022; Wang et al., 2023).

2.4. Economic aspects

The utilization of heat pumps depends greatly on their related costs. Cost-related aspects of heat pumps among other heating technologies depend on various factors including climate condition, geographical location, and market prices. Therefore, the installation and adoption of heat pumps are closely tied to these aspects (Kozarcanin et al., 2020; Vivian et al., 2018). In comparison to alternative heating systems, heat pumps might be more costly. However, this disadvantage may be offset by improved performance, environmental friendliness, and lower operational and maintenance costs.

Compared to other heating technologies to replace the gas-fired boilers, ASHPs are financially a viable option for space heating due to their low initial and operational, and maintenance costs, as well as their efficiency (Renaldi et al., 2017). A similar study in China which conducted a techno-economic investigation, indicated that ASHPs were capable of stably and reliably meet the space heating demands in residential buildings at the ambient temperature of −15 °C. The results of this study showed that ASHPs were the most cost-effective option comparing coal-fired boiler, gas boiler, and direct electric heating mode (Q. Zhang et al., 2017). Additionally, a comparative economic and experimental study of ASHPs and gas-fired boilers in Turkey (Kul & Uğural, 2022) showed that the ASHP could reduce the total life-cycle cost by 26.4% compared with the gas boiler heating system and in turn, reduce the annual energy usage. It was concluded that ASHPs are more affordable in the long term compared with conventional gas boilers.

Heat pump installations in urban areas can benefit from economies of scale. As discussed, urban areas in the Netherlands account for 92.89% of the country's whole population, which gives a greater potential for mass deployment of heat pumps. Moreover, when multiple heat pump installations are carried out in proximity, it facilitates shared infrastructure, such as centralized heating and cooling systems. Furthermore, urban areas often have access to more capital resources than rural areas, making it easier for urban communities to invest in innovative technologies like heat pumps.

In the Netherlands, heat pumps offer promising economic aspects for urban areas. Due to higher population density and building concentration, economies of scale can drive down installation costs and encourage bulk purchasing. The capital availability in cities allows for greater investment in innovative technologies like heat pumps, aided by potential government grants and incentives. The presence of diverse sectors in urban environments fosters supportive synergies for heat pump adoption, facilitating collaboration and integrated energy-efficient urban planning. Leveraging these factors, heat pumps can become a cost-effective and environmentally friendly heating and cooling solution for the Netherlands' urban centers. Also, the presence of diverse sectors like construction, real estate, and renewable energy companies in cities, makes heat pumps more interesting solutions for urban areas. Collaboration between these sectors can lead to integrated approaches to energy-efficient urban planning and development and encourage the incorporation of heat pumps in new constructions or existing buildings.

2.5. Technology acceptance model

TAM is a framework designed to measure the adoption of new technologies based on customer attitudes (Allen, 2020). This theory that was created by Fred Davis in 1989 (Davis, 1989) is recognized as one of the most well-stablished frameworks, widely adopted in research studies related to technology acceptance (Yang et al., 2021). While there are many modifications of the original Davis model, all of them are designed to investigate the key factors that influence consumers' acceptance associated with the adoption and use of technology. The TAM's foundation originates from the theory of reasoned action (TRA) and the theory of planned behavior (TPB). The TAM builds on the TRA and TPB, two comprehensive theories of behavior, to describe the elements that influence consumers' adoption of a wide range of technology (Yang et al., 2021).

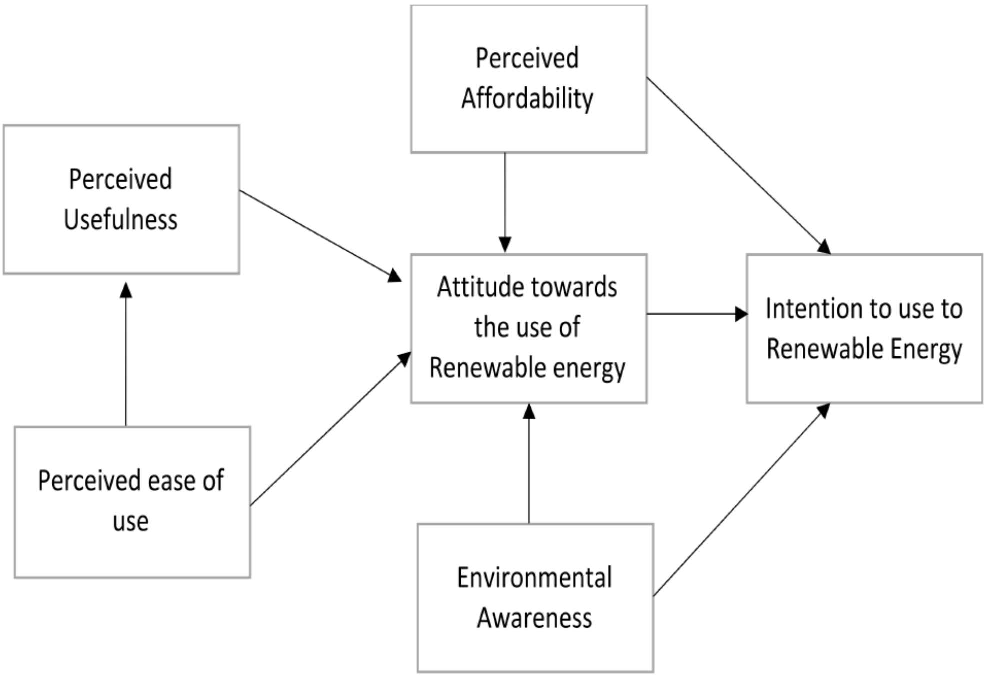

Figure 6: Technology Acceptance Model framework (Yang et al., 2021)

According to the TAM, people's willingness to adopt a technology is greatly impacted by their attitudes towards the technology, which originally goes back to their perceptions of the usefulness and ease of use of that technology (Ducey & Coovert, 2016).

In this sense, this theory is relevant to the heat pump adoption in the Netherlands under the Dutch policy of acceleration the adoption in NL as one of the primary factors of person's willingness to adopt technology is the attitude toward technology (Ajzen & Cote, 2008). Therefore, this study aims to investigate the acceptance of heat pumps, as a technological approach, and finally the acceleration of the adoption in the Netherlands, using an extended model of technology acceptance, which also considers other factors including perceived affordability and perceived environmental awareness (Yang et al., 2021) (see Figure 6). In the following, components from TAM will be elaborated on and below each component, relevant determinants of attitudes towards heat pump adoption related to each category are presented.

2.5.1. Perceived usefulness

Perceived usefulness describes how much a potential user believes that a technology, such as heat pumps, could be useful (Davis, 1989). In the context of heat pumps, perceived usefulness is related to the indicators of energy security and thermal comfort (IEA, 2022a). In this sense, Energy security refers to the ability of heat pumps to provide reliable and continuous heating. Secondly, thermal comfort is related to the extent to which heat pump can provide a comfortable indoor temperature. If potential users perceive that heat pumps can provide energy security and thermal comfort, they are more likely to consider adopting them.

2.5.2. Perceived ease of use

The category of Perceived Ease of Use in the TAM relates to the potential user's perception of how easy or difficult it is to use a technology (Davis, 1989). In the case of heat pumps, this category is related to some indicators, namely the suitability of the building, technical support, and installation skills (IEA, 2022a). These factors influence user's perception of how easy or difficult it is to operate and maintain a heat pump system.

2.5.3. Perceived affordability

Perceived affordability was an extension category added to TAM by (Yang et al., 2021) to address its effect on the attitudes towards an energy technology. This extension relates to the potential user's perception of the costs associated with adopting a technology. When it comes to heat pumps, it is related to the indicator of upfront costs as well as maintenance costs. Heat pumps could be more expensive to install than traditional heating systems. On the other hand, if they can provide savings on energy bills in the long term (IEA, 2022a) it may be another factor influencing users' attitudes. In this sense, the perceived affordability of heat pump systems depends on potential user's perception of the financial benefits of the system and their ability to invest in a more expensive system upfront.

2.5.4. Environmental awareness

Environmental Awareness is another category added to the TAM by Yang et al. (2021). This category addresses potential users' attitudes towards the positive or negative environmental sides of a particular technology. In the case of heat pumps, this category relates to the indicators of phasing out of natural gas and reducing greenhouse gas emissions (Delft, 2022).

2.6. Fuzzy cognitive Mapping (FCM)

Fuzzy Cognitive Mapping (FCM), initially introduced by (Kosko, 1986), is a technique that allows for the organization of qualitative knowledge in a semi-quantitative way. In essence, FCM maps a system schematically through a graph that involves the nature and strength of relationships between concepts of the system (Gray et al., 2015). This enables FCM to analyze and evaluate the relationships between the various components of complex systems (Kosko, 1986). The advantage of employing this method is also linked to its capacity to include a variety of individuals and experts into an approachable and standardized format (Gray et al., 2014). In this method, every concept or variable is represented as nodes connected by arrows, where each arrow's weight indicates how much impact one variable has over the others. These links represent the causal relationships between the concepts. The FCM's linkages between nodes make it possible to analyze and visualize complicated correlations between various variables or ideas in a system. The causality between any two given concepts of C_i, C_j in an FCM map is determined through a weighted arrow. Positive causalities mean an increase in C_i leads to an increase in C_j, and a decrease in C_i results in a decrease in C_j. Negative causalities imply that an increase in C_i results in a decrease in C_j, and a decrease of C_i leads to an increase in C_j. Weights of the causalities are in the range of [−1, 1]. FCM modeling uses non-linear transfer functions in its operation. Two widely used types of transfer functions for FCM are the sigmoid and hyperbolic tangent functions. The sigmoid function makes sure that the measured value of each concept falls within the interval of [0, 1], while the hyperbolic tangent function allows for the possibility of negative causalities as well, expanding the interval to [-1, 1]. The formula of sigmoid and hyperbolic functions is presented in equations 1 and 2, respectively (Kokkinos et al., 2020). Since both positive and negative concepts are involved in this research, the hyperbolic tangent function is employed.

$$f(x) = \frac{1}{1 + e^{-\lambda x}} \quad (1)$$

$$f(x) = \tanh \lambda x \quad (2)$$

A FCM is a fuzzified, computable qualitative model of how a given system operates.

The capabilities of FCMs in dealing with systems consisting of concepts with different natures, makes them appropriate for modeling the socio-technical complexity that is present in the heat pump adoption system, as they allow for more flexibility and accuracy than other methods, e.g., statistics-based methods, such as linear regression.

In recent years, FCM methodology has also been applied in energy topics. One example of the application of FCM in energy topics, is the research conducted by Jetter & Schweinfort (2011), in which the feasibility of FCM on solar panels through different scenarios is explored to help scenario planners. This research underlines the FCM's capabilities in interpreting what the future might contain despite the simplicity of the underlying causal maps and that once the FCM models accurately reflect the scenario planners' mental models (which may then have been modified), they can be used to assess strategic alternatives and wildcards in various scenarios. Another example of the application of FCM is the research that was performed at the University of Twente on the energy transition of district heating systems in the Netherlands (Shahbazi, 2022). This research serves as a decision support tool for the policy maker in the context of district heating in the Netherlands. In another research project, FCM was applied in the context of the electricity production from natural gas and the consequences of the 2022 European delegated regulation on the Dutch energy transition was studied in this research (Kamali, 2022).

3. Methodology

3.1. Research strategy

In this study, the public's attitudes of heat pump technology in urban NL are measured using the TAM. To operationalize the TAM in this research, the key components connected to each category of TAM are identified and then incorporated into the FCM. At the start, based on background research, literature reviews, and interviews with key informants, determinants are created for each category of the TAM and given in the survey form to examine the public’s attitudes and expert standpoints. When the FCM model is complete, these indicators will be incorporated as the system's main driver. These indicators will also be used as IF-Input for developing scenarios in the final FCM models to further analyze the effects of each scenario simulation on the technological uptake of heat pumps.

The FCM software that is used in this research is Mental Modeler (www.mentalmodeler.com). Mental modeler is an online software that is used to create the FCM and visualize the relationships between the concepts and perform the analysis based of what-if scenarios. The conclusion of this research would be summarizing the research findings, their significance, and implications for practice. Finally, limitations of the study and recommendations for future research directions are provided. Figure 7 visualizes the steps of the research strategy.

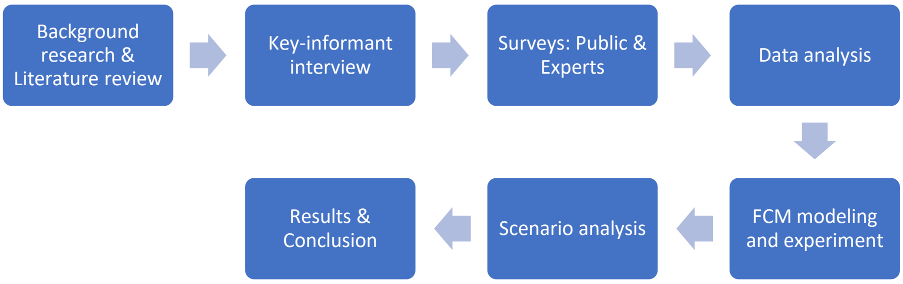

Figure 7: Research strategy

3.1.1. Data collection

The data collection methods in this research are qualitative. The required data is collected from literature reviews, interviews, and surveys. The interview is conducted with the key informant to acquire detailed and in-depth understanding of technical issues related to heat pumps. Residents’ concerns are identified through a survey and driving factors to these concerns are gathered through a survey from energy transition experts.

This research is a case study in the Netherlands. According to Yin (2009), a case study is an empirical investigation that looks at a current phenomenon in its actual setting, particularly when the distinctions between phenomenon and setting are not clear. In the present research, Leeuwarden is selected as a case study. While it is necessary to acknowledge that the city of Leeuwarden may not fully represent every location in the Netherlands, it nevertheless serves as a representative case for large urban centers in the country. The sampling strategy involved surveys from the residents in Leeuwarden. The survey was developed online with the help of the QUALTRICS software and disseminated online and in-person. To determine the planned sample size for this study, the Slovin method (Sciencing) was used with a margin of error of 10% (see Equation 3). With about 91000 people living in Leeuwarden in 2022, the sample size was aimed to be 99 people that should respond to the survey.

$$n = \frac{N}{1 + Ne^2}$$
$$n = no. of\ samples$$
$$N = total\ population \quad (3)$$
$$e = margin\ of\ error$$

Then, the first sub-research question concerning key factors affecting the decisions of urban households to adopt heat pumps, will be answered through the data acquired from the interview and surveys.

3.1.2. Data analysis

Method of the data analysis in this research is scenario analysis using FCM. The indicators in the FCM are factors which influence residents' attitude and the driver indicators that are gathered from expert surveys. These experts also determine how the indicators would affect each other by specifying the importance and relation of each indicator. In this way, the collected data will be converted from qualitative to quantitative data to enable analysis using the Mental Modeler software. Strategies that will be employed in this research are first to outline how literature review and surveys will provide information to be used in FCM, and secondly, to outline how the FCM simulations will be used after the model is ready is as follows:

(I) Strategy for developing FCM modeling

a) Concepts (knowledge content) of the FCM model: Literature review will be the initial source to identify key concepts related to heat pumps to develop the basic FCM model. Afterwards, the findings from surveys and interviews from both the public and experts will be used to support the initial model. The surveys will also include open-ended questions to ensure that all relevant concepts are captured.

b) Links (causal relationships) of the FCM model: The literature review will be the basis for identifying the causal relationships between the different concepts of the FCM model. Afterwards, findings from surveys and questionnaires will be used to support the initial developed linkages. To elaborate more, the experts will be asked to provide upstream linkages between the concepts, and the public concerns found from the surveys would consist downstream linkages to the attitude concept.

c) Weights (strength of interaction) of the FCM model: After the links are created, the experts' and residents' surveys will be used to determine the strength of interaction between the concepts. In this sense, the experts will be asked to rate the strength of interaction between the different upstream concepts on a Likert scale and the public will be asked to rate the importance of downstream concepts that influence their attitude (in direct connection with that).

d) Scenarios: The scenarios will be created based on the findings from surveys and questionnaires derived from changes expressed by the participants' wants and needs. Different combinations of changes in the concepts will be tested to assess the influence of different technical, economic, and environmental factors on the whole system.

(II) Experimental Strategy:

After the model is ready, FCM simulations will be conducted to explore different scenarios. To this end, the scenarios will be developed based on the data gathered from the interviews and surveys according to the changes expressed by the participants' wants and needs from the experts and public point of view to meet their concerns. These scenarios will be used to explore the potential impacts of different policy options if the policy maker goes to implement them. So, the simulations could produce policy recommendations based on the results of the different scenarios. As said was earlier above, the FCM software used in this research is Mental Modeler (www.mentalmodeler.com), which is used to experiment socio-technical what-if scenarios.

The second sub-research question concerning techno-economic changes to improve residents 'attitudes towards heat pumps will be examined and answered through the scenario analysis as mentioned above.

3.1.3. Ethical considerations

When conducting the interviews, the interview protocol is assessed on its ethical standard prior to the implementation of the interviews to prevent any ethical wrongdoing. The assessment of the ethical standards concerning the research is done by the BMS Ethics Committee. Only after approval do the interviews take place.

Before the interviews, a Consent Form is provided to each responsible person to get their written approval. For online interviews, the interviewee is asked for consent to audio record the interview. Besides, they are informed about the procedure in advance so that they have the option to stop at any time if this is their wish. If requested by an interviewee, their names are not mentioned. In general, the interviewees are mostly mentioned in their professional capacity, by mentioning their position and job title.

When conducting surveys, the online platforms of the University of Twente are used to store the data. The consent form is provided at the beginning of each survey, in order to ensure all ethical guidelines are followed.

3.2. Interview and surveys

3.2.1. Key informant interview

The goal of this interview was to gather insights and information from a key informant, in the domain of HVAC, combustion systems, and heat pumps. regarding the topic of heat pumps and the main challenges that consumers face when considering the purchase of heat pumps. The interview aimed to explore various aspects related to the use of heat pumps, including their benefits, costs, energy efficiency, technical barriers, and consumer preparations for installation. By these questions I sought to gain a comprehensive understanding of the factors influencing the uptake of heat pumps. The interview was conducted in English online via Microsoft Teams. The interview questions can be found in the Appendix of this thesis.

The interview started with asking a question to understand the perceived advantages of heat pumps from the consumer's perspective. The second question aimed to explore the upfront costs associated with heat pumps in order to understand the financial considerations that consumers may have. By investigating the expenses involved in purchasing and installing heat pumps, potential barriers related to affordability were aimed to be identified. Question 3 sought to compare the maintenance costs of heat pumps with traditional gas boilers. Understanding the ongoing expenses related to maintenance was essential for assessing the long-term affordability and feasibility of heat pumps. Question 4 aimed to examine the impact of heat pumps on energy bills and compare the energy consumption and associated costs between heat pumps and gas boilers, and whether heat pumps provide savings or improvements in terms of energy efficiency. Then in question 5, it was asked about technical or logistical barriers that can prevent the widespread adoption of heat pumps. This question focused on identifying the obstacles and challenges that may impede the widespread adoption of heat pumps, such as installation complexities, availability of skilled personnel, or compatibility with existing infrastructure. And in the last question it was asked about if the consumers need to prepare their dwelling prior to installation of heat pumps to explore necessary modifications homeowners may need to take before installation and identify additional barriers or inconveniences that could affect the decision-making process by the consumers. The information collected in this interview helped in generating the initial FCM model.

3.2.2. Residents' survey

The public survey was conducted among Leeuwarden residents to gather their attitudes, concerns, as well as their awareness about heat pumps. It was made sure to give information to the participants that this survey is designed for residents of Leeuwarden as Leeuwarden is the case study in this research, and participation is only for residents aged over 18 years old and was entirely voluntary. The survey was made available in both English and Dutch languages. The survey began with an introduction providing initial information about the survey's purpose and goals. It also included a description of what a heat pump is and how it is used for heating residential buildings. Additionally, a picture of a typical heat pump unit was included to visually familiarize participants with its appearance. The first questions were designed to collect demographic information about gender, age, work occupation, annual income, residence situation, and household size. In question 6, people were asked whether they own their living building, or they are tenants. This question is designed because the ownership of the building would be an issue when it comes to deciding on a new device installation on the building. This could a source of split of incentives between homeowners and tenants (Bagaini et al., 2020; Castellazzi et al., 2017). Tenants must have a landlord who would be prepared to invest. Then, question 8 evaluated prior knowledge of participants about the technology. In question 9 was designed to understand the technology currently in use at homes and then in question 10 it was asked the extent to which it is important for participants to have a choice in the heating system for their living place. This question is important when it comes to individual choice in selecting a heating system and it is also related to affordability of heat as a service. Then questions 11, 12, and 13 were the main questions to address all the four categories of TAM, meaning perceived affordability, perceived usefulness, perceived ease of use, and environmental concerns. In these questions participants were asked to rate the influence of various factors, such as in-home thermal comfort, greenhouse gas emissions reduction, cost considerations, and noise pollution to examine the extent to which each factor is a place of concern for residents. And finally, question 14 intended to assess participants' overall willingness to adopt or retain a heat pump. The English version of survey questions could be found in the appendix.

3.2.3. Experts' survey

To determine the strength of the interrelations and interdependencies of the FCM concepts, a varied group of experts were surveyed to get their perspectives on the environmental, social, economic, and technological elements related to the development of heat pumps. The diversity of interviewed experts, ranging from environmentalists to economic analysts, all of whom possessed expertise in energy transition, ensured that the subject was examined from various perspectives. The professions and areas of expertise of the surveyed experts can be found in the appendix. In total, experts answered 22 interdependency-oriented questions. It should be noted that the number 22 resulted after merging similar concepts that were closely aligned.

Regarding the survey procedure, it started by outlining to the experts the goal of this survey and the relevant concepts to heat pumps from a TAM perspective, as well as how the causal links between concepts work in an FCM in the simplest language. The participants were able to determine the strength of causality after being given a statement about the relationship between two concepts. The values allocated to causalities (weights) where in the fuzzy spectrum (extremely, very, moderately, slightly, not at all). After the collection of surveys, the Likert scores are mapped to the FCM map, which is shown in Figure 8, to assign the weights of causal relationships. The survey questions can be found in the appendix.

3.3. FCM generation

This section centers around the connection between concern-based indicators discussed earlier and the concept of public attitudes. As illustrated in Figure 8, these concepts have been positioned near the center of the FCM in green, pointing toward the attitude concept. Upstream concepts (colored purple) are linked to these concern-based indicators based on their causal relationship. Concepts of the FCM that could be translated to the knowledge content of the model, are driven from literature review and data gathered from surveys in this research. Table 1 lists these concepts and categorizes them. The FCM comprises of a total of 15 components.

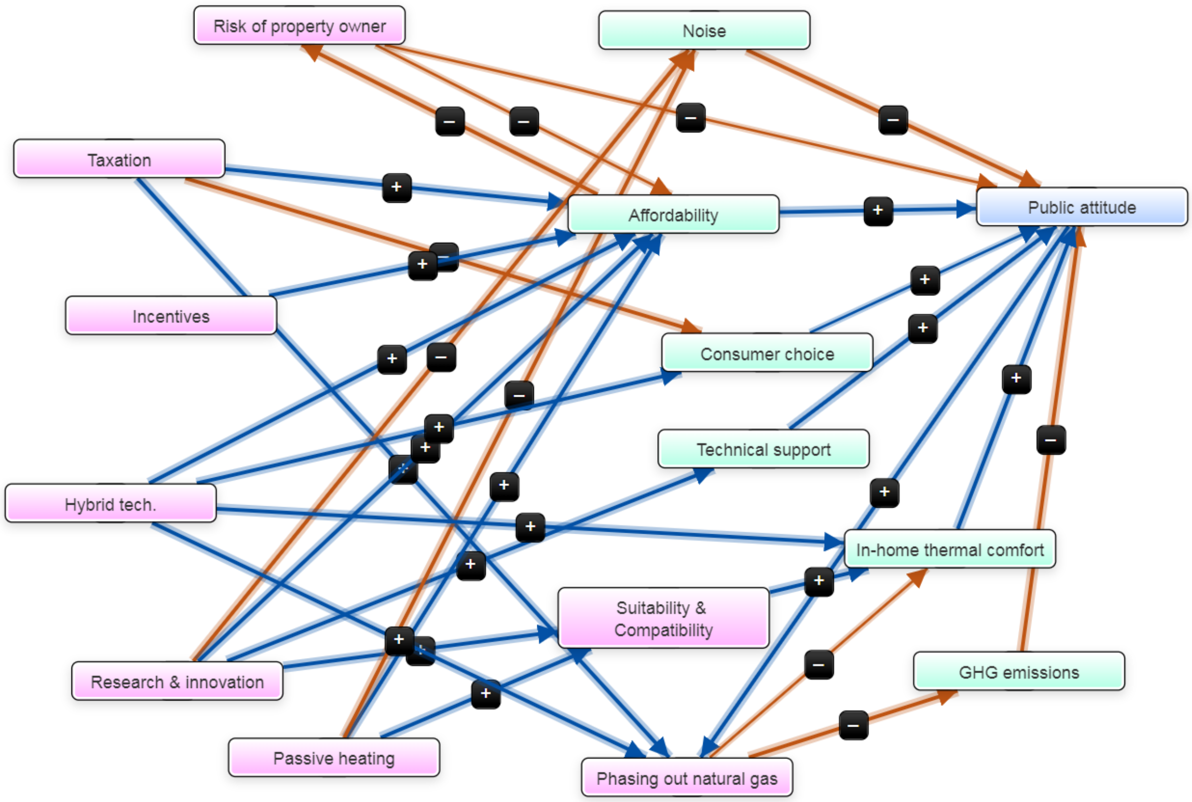

Figure 8: FCM graph: components, and their relationships

Table 1: List of the Concepts

Category	Concept number	Concept name
Social	C1	Public attitude
	C2	Risk of property owner
Environmental	C3	GHG emissions
	C4	Phasing out natural gas
	C5	Noise
Technological	C6	In-home thermal comfort
	C7	Consumer choice
	C8	Research & innovation
	C9	Suitability & Compatibility
	C10	Technical support
	C11	Passive heating
	C12	Hybrid tech.
Economic	C13	Affordability
	C14	Taxation
	C15	Incentives

4. Results and discussion

This chapter presents the findings from the interviews and surveys. The key informant interview helped in identifying the main concepts related to heat pump adoption and informed the subsequent surveys. The residents' and experts' surveys provided the input data for the FCM model.

4.1. Key informant interview

This interview was intended to explore the main challenges that consumers face when considering the purchase of heat pumps. The interviewee was an expert in HVAC, combustion systems, and heat pumps.

According to the informant interviewee, the benefits of heat pumps for consumers were highlighted: first, the ability to provide the same heat with lower environmental impacts and second, the elimination of gas usage in favor of electricity. One upfront action associated with the electric heat pumps as revealed was the need for insulation of the house. Maintenance costs for heat pumps were found to be comparable to those of gas boilers, indicating that consumers would not experience a significant difference in this regard. Regarding the impact on energy bills when using heat pumps compared to gas boilers, it was noted that it would depend on the relative prices of electricity and gas. Finally, the informant highlighted the need for outdoor space to install the heat pump's outdoor unit. The insights gained from the interview provided a deeper understanding of the main concepts related to heat pumps, enhancing the development of the initial conceptual model of the FCM.

4.2. Findings from residents' survey

4.2.1. Demographic findings

This survey successfully reached out to a total of 103 residents of Leeuwarden. Among the 103 participants, 55 surveys were completed by males, 46 surveys by females, and 2 participants preferred not to disclose their gender (see Figure 9). The distribution of respondents indicates that both females and males were effectively engaged in the survey, with a representation of approximately 46% and 53% respectively.

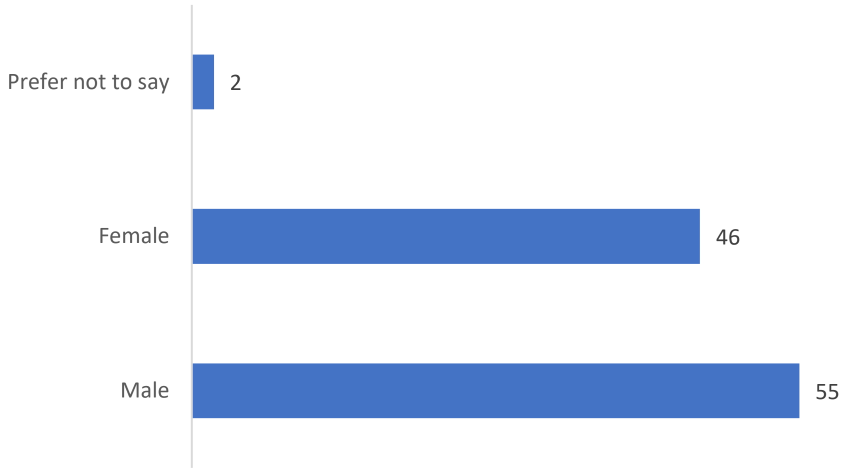

Figure 9: Gender distribution of respondents

As it is illustrated in Figure 10, the age groups of respondents are diverse, with a relatively higher representation of individuals in the 31-45 years old category which comprised 39% of the respondents.

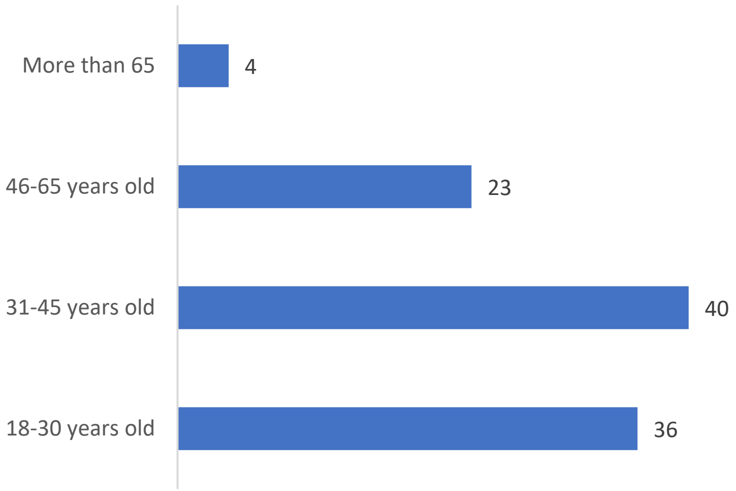

Figure 10: Age distribution of respondents

Examining the participants' work occupations, it is evident that out of the 103 respondents, the majority, accounting for 66%, were employed (68 participants). Following this, 25% of the respondents were students (26 participants), and 9% were retired (9 participants) (see Figure 12). This distribution highlights the significant presence of working individuals among the survey respondents. This is a valuable finding as employed individuals typically possess decision-making power regarding the adoption of a heating system for their homes.

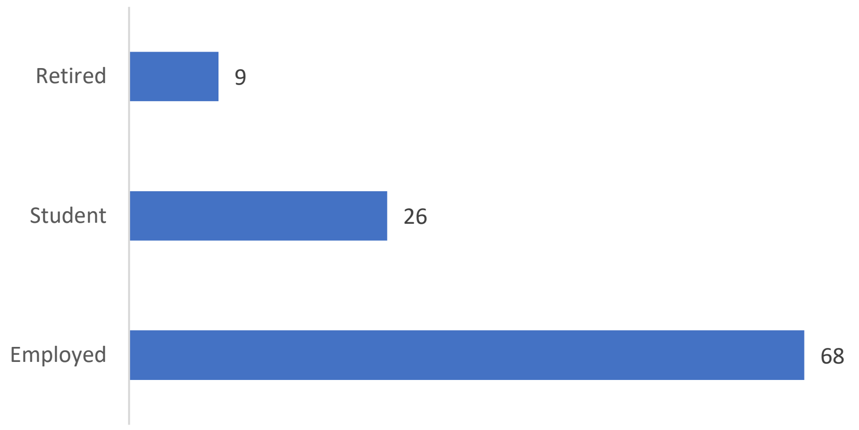

Figure 11: Occupational distribution

Among the respondents who provided information, a diverse range of income levels was observed. 23 out of 103 respondents preferred not to disclose their income (see Figure 12). Although this limited the available data, it was essential to respect participants' privacy. Among the respondents who provided their annual income data, there were various income categories represented. The highest proportion was observed in the range of 40,000 to 60,000 euros, with 27 respondents falling within this category.

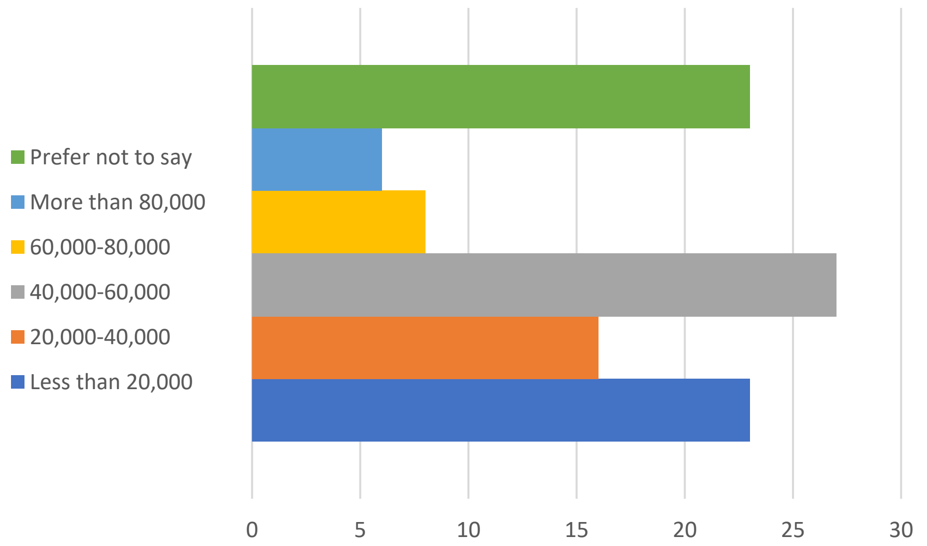

Figure 12: Income range distribution

Answers to the question about residence situation showed that a higher percentage of respondents (61%) own their residence, an apartment, or a house (see Figure 13). This group of homeowners have more autonomy and control over their housing decisions, including investments in energy-efficient technologies. On the other hand, about 39% of the respondents were tenants. This group may face additional considerations, which could introduce potential barriers or split incentives between the property owner and the tenant. The type of building (house or apartment) could be a concern regarding the physical space required for heat pump installations. However, the responses did not show any significant difference between the answers provided by these two groups.

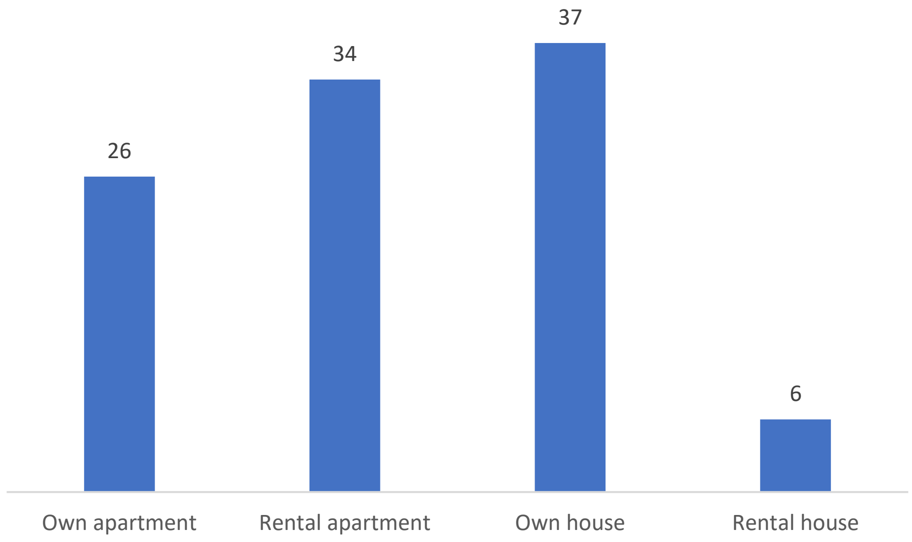

Figure 13: Residential situation distribution

Acquiring information on the current heating systems used by the respondents as it can be seen in Figure 14, revealed that a significant majority (63 out 103) use gas boilers as their primary heating system for their homes. 9 participants reported using heat pumps, followed by 8 participants stated using district heating, and 2 reported using electric heaters. Respondents were also given a choice to specify if they were using another type of heating system. In response, 21 participants chose this option and all of them indicated that they did not know what type of heating system they currently had in their homes. This finding highlights a lack of awareness or knowledge about the heating systems among these respondents.

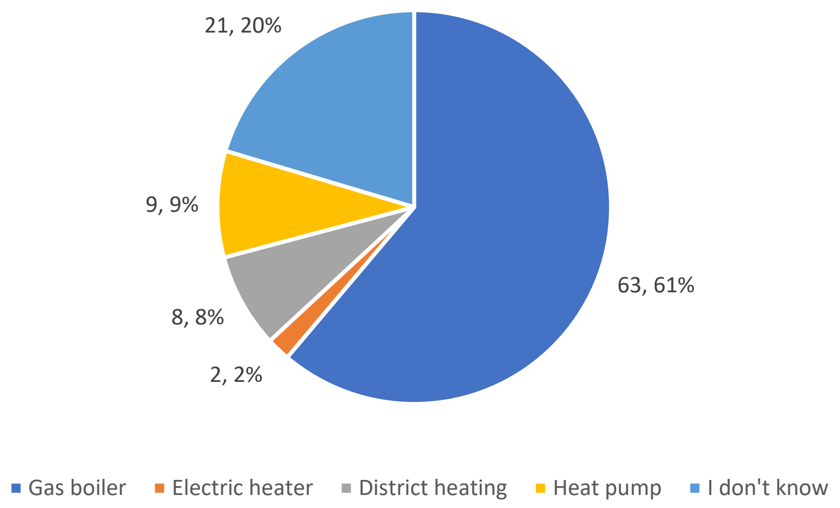

Figure 14: Distribution of heating system installation types among participants

4.2.2. Prior knowledge about heat pumps

The findings from the survey revealed that out of total 103 respondents, 69 participants (67%) indicated prior knowledge about heat pumps, while 34 respondents (33%) were not familiar with them before the survey (see Figure 15).

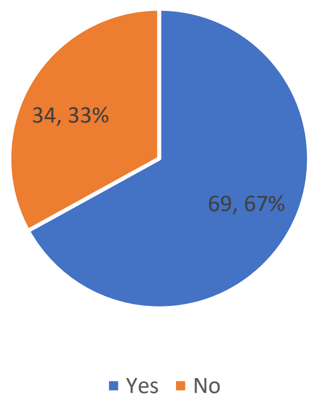

Figure 15: Before this survey, did you know about heat pumps?

This result shows a majority of the participants had some level of familiarity with this technology. However, there is still a portion of respondents who were not familiar with heat pumps. This suggests the potential to enhance their acceptance among a wider audience by providing relevant information about the benefits and functionality of heat pumps.

4.2.3. Findings on concern-based indicators

4.2.3.1. Economic considerations

Inquiring about the participants' level of economic concerns, the survey aimed to capture insights from both property owners and tenants. The responses to questions regarding upfront costs and return on investment primarily reflect the perspectives of property owners, as they hold the decision-making power in these matters. The question concerning operating costs, particularly energy bill expenditures, includes responses from both property owners and tenants.

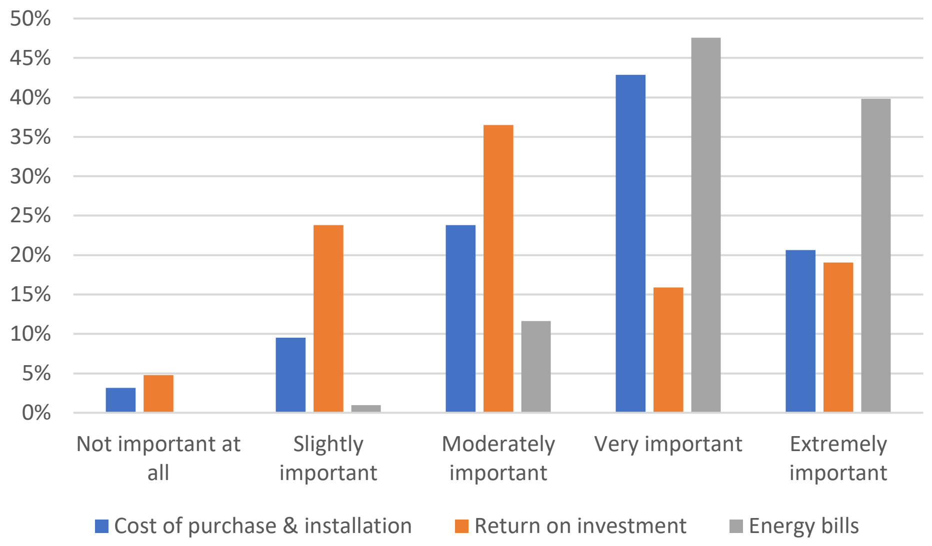

Figure 16: Residents' economic considerations

According to Figure 16, when considering the cost of purchase and installation, most respondents (43%) rated it as "Very important". This suggests that the upfront investment required for purchasing and installing a heat pump is a crucial factor for individuals when considering this technology.

In terms of return on investment, a smaller percentage of participants (16% and 19%) considered it "Very important" or "Extremely important", and a larger proportion (37%) rated it as "Moderately important." This finding shows that participants are aware of the long-term financial benefits that heat pumps can suggest.

Energy bills emerged as the highest significant cost factor among the respondents. Almost half of the participants (48%) rated it as "Very important," and an additional 40% considered it "Extremely important." This indicates a strong emphasis on the potential impact of heat pumps on reducing energy bills and participants recognize the importance of energy efficiency and cost savings when evaluating their heating options.

4.2.3.2. In-home thermal comfort

The survey findings reveal that in-home thermal comfort is a superior consideration for residents when it comes to their heating choices. A significant majority of respondents, representing nearly 88% of the total participants, rated in-home thermal comfort as either very important or extremely important (see Figure 17).

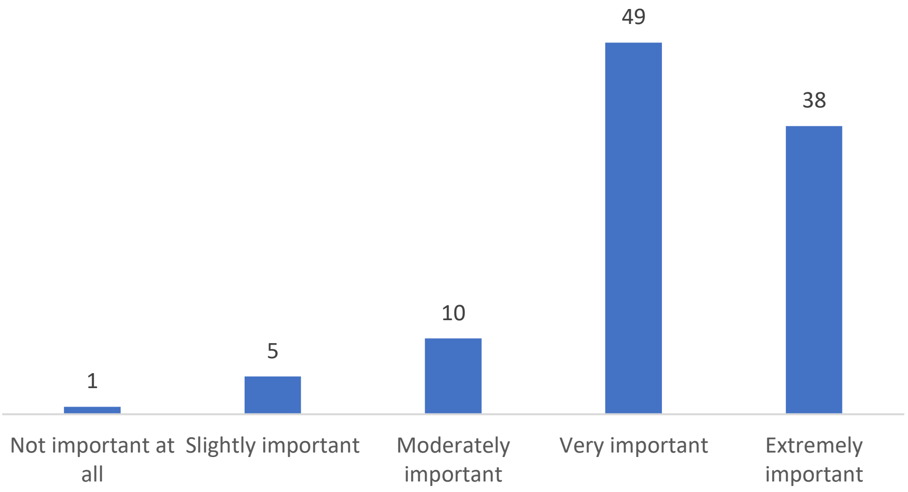

Figure 17: In-home thermal comfort concerns

This high level of importance placed on in-home thermal comfort highlights the significance residents attach to creating a comfortable living environment at their homes and further underscores its significance in the decision-making process.

4.2.3.3. Environmental concerns

The survey findings indicate that a substantial number of participants consider sustainability and reducing environmental impact to be a relevant factor in their heating choices. As it is illustrated in Figure 18, out of the 103 respondents, a majority rated this factor as either very important (31) or extremely important (26). The age distribution of the participants shows older people to be rather more sensitive to ambient temperature and young people to be more environmentally aware.

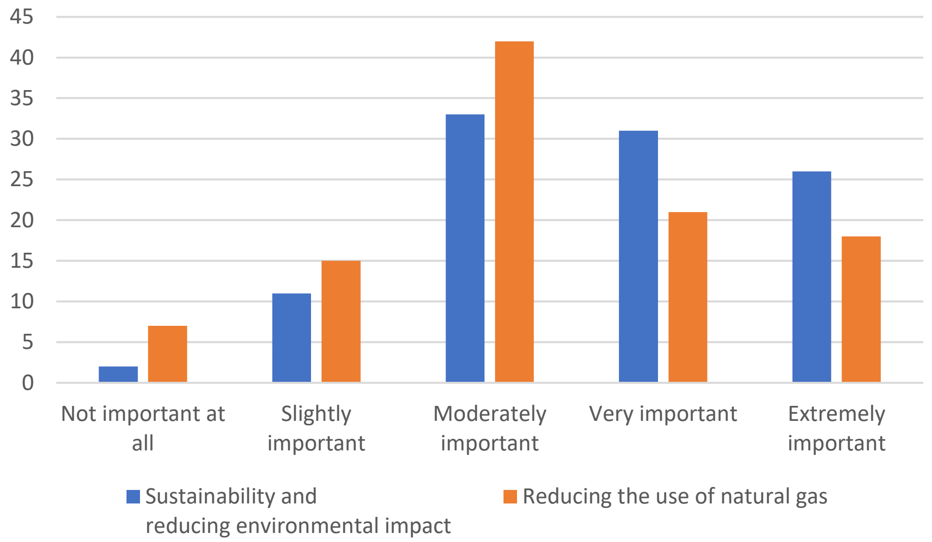

Figure 18: Residents' environmental concerns

Reducing the use of natural gas was also deemed significant by a considerable portion of the participants. Although the distribution of ratings differed slightly compared to sustainability and environmental impact and most of the respondents (42 out of 103) rated it as moderately important.

4.2.3.4. Noise pollution

Regarding noise pollution concern, most of the respondents rated noise pollution as a moderately to extremely important factor in their considerations. According to Figure 19, out of 103 responses, 38 individuals rated it as "Moderately important", 25 individuals as "Very important", 30 individuals as "Extremely important", and for only 10 residents it was less of a concern.

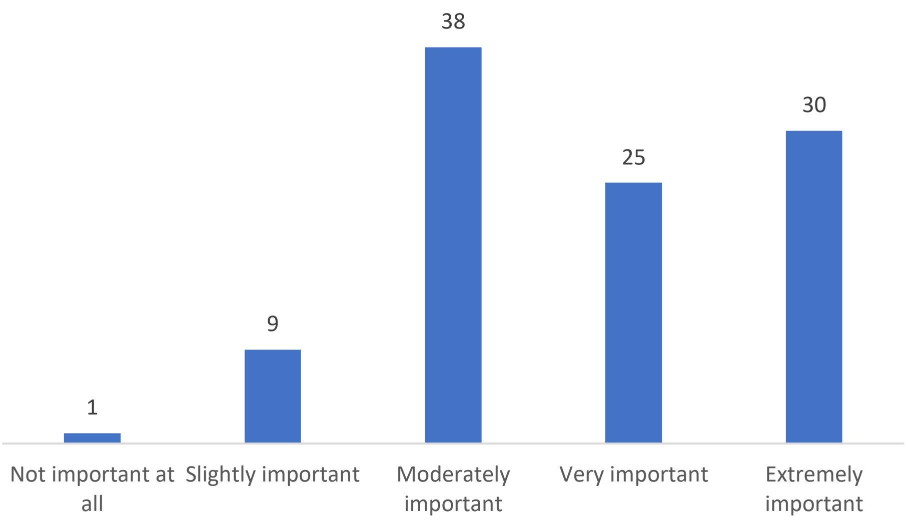

Figure 19: Residents' noise pollution concern

The fact that approximately 90% of respondents rated it as moderately important or higher indicates a significant level of concern regarding noise levels within their homes.

4.2.3.5. Consumer choice

This indicator aimed to understand the level of importance residents placed on having the autonomy to select their preferred heating system. The responses from the participants are presented on Figure 20.

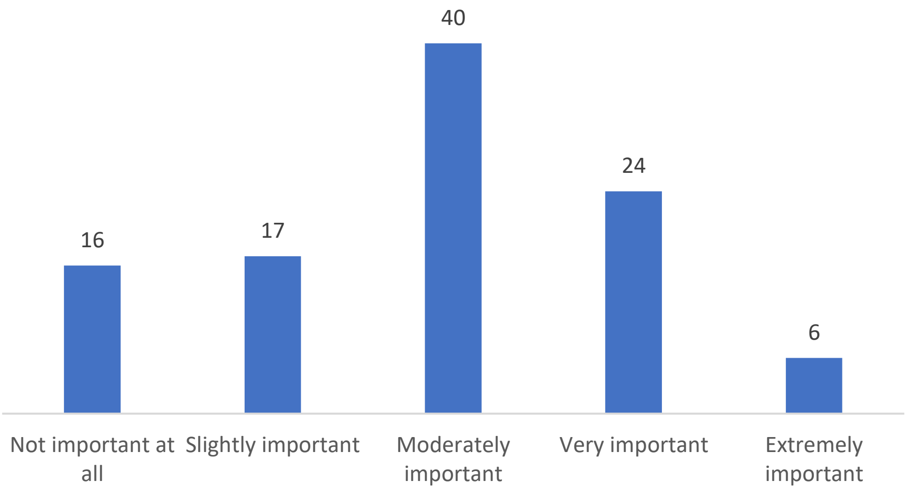

Figure 20: Consumer choice responses

As it can be seen, most respondents (40 individuals) rated consumer choice as moderately important. Additionally, 24 individuals considered it very important, while 6 individuals considered it extremely important. On the other hand, it was less of a concern for totally 33 residents. The combined total of individuals who rated it as moderately important, very important, or extremely important accounts for 70% of the respondents that indicates a desire for consumer choice in heating options. The importance placed on consumer choice can be attributed to several factors. For instance, residents may prioritize the ability to select a heating system that aligns with their specific heat level needs, some individuals may prioritize energy efficiency, and others may prioritize cost-effectiveness.

4.2.3.6. Technical support

This indicator aimed to gauge the significance of seeking professional advice and assistance for installation and maintenance of heat pumps. As it can be seen in Figure 21, the majority of respondents (41 out of 103) considered this aspect to be moderately important, followed by 24 who implied it very important. This finding emphasizes the need for reliable consultation and skilled workers in the field to support residents if they decide to uptake heat pumps.

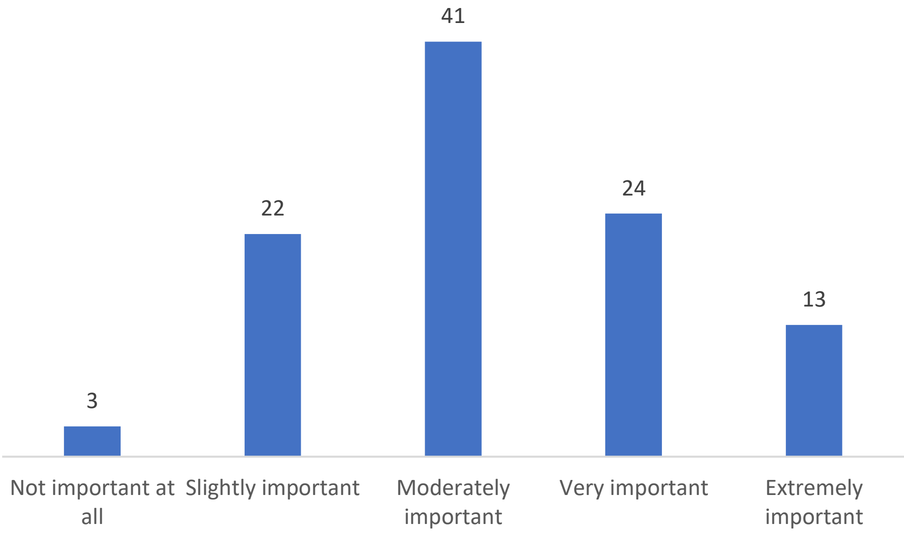

Figure 21: Residents' technical support concern

4.2.4. Summary of the residents' survey findings

As seen, this survey aimed to gather insights into the attitudes and concerns of the residents regarding heat pumps. The survey included a range of questions covering various aspects, such as awareness of heat pumps, financial considerations, environmental concerns, and other relevant factors identified from the TAM. Figure 22 represents the importance a summary of rating assigned by respondents to various concern-based factors in this survey.

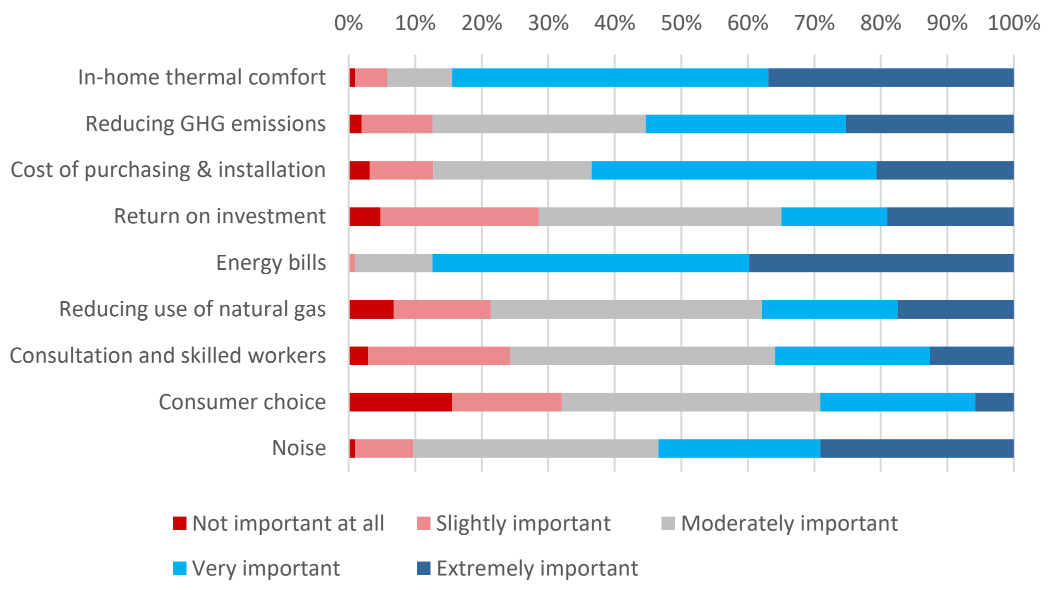

Figure 22: Importance ratings of factors related to heat pumps expressed as % of respondents

As observed in the survey, gas boilers were the most prevalent heating system among respondents currently in use, with a total count of 63. It is noteworthy that this number represents approximately 77% of respondents who were aware of their current heating system. The 23% who did not know about their heating system, possibly are not the person responsible in their household for heating or they live in an apartment block. The proportion of heat pump users based on the subset of respondents who knew their current system in the survey is 7%. These findings align with the latest published data on residential heating installations in the country, which indicate a share of approximately 82% for gas boilers and around 11% for heat pumps in the total housing stock (CBS, 2022a). This suggests that the survey sample is representative of the wider population in terms of heating systems.

Moreover, the survey revealed that 55 participants (53%) expressed their unwillingness to adopt heat pumps. This highlights the social acceptance challenges that heat pumps still face within the surveyed population. Looking at the profile of those with positive or negative outlooks, residents who prioritized environmental concerns had more positive attitudes towards heat pumps, while those highly concerned about upfront costs and noise pollution showed hesitance towards adoption. Both respondents with positive and negative attitudes valued in-home thermal comfort almost at the same level.

Additionally, in a section of the survey, participants were also asked to specify their main reason if they were to have a heat pump, and they were provided with various options. Among the respondents, 57 individuals expressed their primary motivation as "Saving on energy bills."

Additionally, 17 respondents cited "Contributing to sustainability and reducing environmental impact" as their main reason, and 22 out of the 103 participants indicated "Financial incentives" as their primary motivation. Combining the two financial options shows a share of 76% among all responses. This underscores the significant role of cost considerations in the adoption of heat pump technology. When comparing this to the high importance given to environmental concerns (55% of responses rated it as very or extremely important), it becomes evident that while residents prioritize environmental issues, cost considerations still take precedence.

4.3. Assessment of experts' survey in FCM

After the collection of surveys, the data is applied in the FCM model. The casualties of the FCM are derived by defuzzification of survey responses to identify the degree of causality between concepts. The confidence ratings for each of paired concepts are shown in Table 2. In this table, the causality between any two concepts of C_i, C_j is represented. As said before, positive causalities mean a direct relationship between the two concepts, and conversely, a negative causality implies an inverse relationship between the two concepts. Weights of the causalities are in the range of [−1, 1]. The definitions for concepts are provided in Table 4.

Table 2: FCM causalities

C1,C4	0.63	C6,C1	0.79	C10,C1	0.55	C12,C13	0.56
C2,C1	-0.38	C7,C1	0.47	C11,C5	-0.56	C13,C1	0.82
C2,C13	-0.44	C8,C5	-0.56	C11,C9	0.63	C13,C2	-0.56
C3,C1	-0.67	C8,C9	0.63	C11,C13	0.81	C14,C4	0.69
C4,C3	-0.63	C8,C10	0.69	C12,C4	0.56	C14,C7	-0.63
C4,C6	-0.19	C8,C13	0.63	C12,C6	0.5	C14,C13	0.56
C5,C1	-0.68	C9,C6	0.63	C12,C7	0.63	C15,C13	0.75

According to the causality weights given in Table 2, the highest weight is associated with the impact of passive heating techniques on affordability. Interestingly, when considering all concepts influencing affordability, which took the highest precedence among all other concerns by residents, the experts have identified passive heating techniques as having the highest value among other factors, including incentives, taxation, research & innovation, and hybrid heat pumps. This is consistent with the multiple reports, which emphasize that passive heating techniques can significantly reduce energy bills (Dwell, 2017; the Australian Government, 2020; Tungnung et al., 2023), which again among all cost considerations of residents was found as the most important one. On the contrary, the lowest score is associated with the link between transitioning away from natural gas in the heating sector and in-home thermal comfort, where experts found its negative impact to be only minimal.

Afterwards, the input data is used to calculate:

- Total number of components
- Total number of connections
- Indegree/ Outdegree of each component
- Connections per component
- Component type (driver, ordinary, receiver)
- Centrality
- Complexity
- Density

Table 3 displays the FCM's overall statistics and concept-specific individual attributes mentioned above are presented in on Table 4.

Table 3: FCM's general statistics

FCM properties	**Value**
Total components	15
Total connections	28
Density	0.133
Connections per component	1.867
Number of driver components	5
Number of receiver components	0
Number of ordinary components	10
Complexity score	0

The concepts are categorized in four groups, including: a) Social, b) Environmental, c) Technological, and d) Economic. The FCM (the graph presented in Figure 8) shows a 0.133 density score and zero complexity. Complexity score is the ratio of receiver concepts to transmitter concepts. As there were no receiver component in the developed FCM, the value of the complexity was zero. Subsequently, density index represents the degree of interconnectedness among variables, measured by the ratio of connections to the maximum possible connections (Özesmi & Özesmi, 2004).

Table 4: Categorization and metrics in the FCM

	Concept number	Concept name	Indegree	Outdegree	Centrality	Type
Social	C1	Public attitude	4.36	0.63	4.99	ordinary
	C2	Risk of property owner	0.56	0.82	1.38	ordinary
Environmental	C3	GHG emissions	0.63	0.67	1.3	ordinary
	C4	Phasing out natural gas	1.88	0.82	2.7	ordinary
	C5	Noise	1.12	0.68	1.8	ordinary
Technological	C6	In-home thermal comfort	1.32	0.79	2.11	ordinary
	C7	Consumer choice	1.26	0.47	1.73	ordinary
	C8	Research & innovation	0	2.51	2.51	driver
	C9	Suitability & Compatibility	1.26	0.63	1.89	ordinary
	C10	Technical support	0.69	0.55	1.24	ordinary
	C11	Passive heating	0	2	2	driver
	C12	Hybrid tech.	0	2.25	2.25	driver
Economic	C13	Affordability	3.75	1.38	5.13	ordinary
	C14	Taxation	0	1.88	1.88	driver
	C15	Incentives	0	0.75	0.75	driver

In this FCM, "Public attitude" represents the ultimate objective, which is the perception and acceptance of heat pumps among the general public in terms of their willingness to adopt and support this technology. The concept of "Risk of property owner" relates to the concerns and uncertainties property owners may have regarding the installation and operation of heat pumps in their properties.

As observed in Table 4, the most central component in the map is "Affordability" with the score of 5.13. The concept of "Public attitude" attains a centrality score of 4.99. It is noteworthy to mention that while connection number per component for both concepts is equal to eight and public attitude is the final goal of the system, "Affordability" attains the highest centrality, which suggests its pivotal role in shaping the dynamics of the system. Centrality measures the relative importance of a concept within an FCM. In the FCM, the centrality of each concept is determined through algebraic calculation that takes into account its overall influence on the entire map, considering all related positive and negative causalities, or alternatively, by assessing its individual influence indicated by positive (+) or negative (−) values that highlight the conceptual causality or relationship with other concepts. A concept with higher centrality holds more significance and weight in shaping the dynamics of the overall model (Gray et al., 2014; Kosko, 1986). In this regard, "Affordability" and "Public attitude" have attained the highest centrality, representing the most important concepts in the FCM in this way.

4.4. Scenario analysis

The “what-if” scenario analysis of FCM enables the assessment of alternative scenarios and could assist policy makers in decision making process about the effects of the policies taken under those scenarios (Kosko, 1986, 1993). In the context of heat pumps, the role of decision-making among alternative scenarios will be important when it comes to a successful energy transition and phasing out of natural gas. Constructed on the problem statement and the research questions defined, the preferred state in this research is increasing positive attitudes of residents towards heat pumps while transitioning away from natural gas. Looking at the future energy plans and strategies of the Netherlands, the country is aiming at several solutions that also address heat pumps.

The Netherlands is currently realigning its overall energy research, development and demonstration (RD&D). To this end, a new framework which outlines 13 Multiannual Mission-Driven Innovation Programmes (MMIP) for research and innovation is putting in place (IEA, 2020). The MMIPs’ research targets at different levels including fundamental and industrial research. It also considers expertise and human capital. Each of MMIPs focuses on a specific technology or sector. Among those, the focus of MMIP 4 is to foster innovations of sustainable heating systems. Within the framework of MMIP 4, it is emphasized on the importance of introducing heating options that align with the comfort of users (including noise and thermal) and affordability. "Quiet, compact, smart, and cost-effective heat pumps" is one the defined sub-programmes under MMIP 4 (IEA, 2020).

Gas, electricity, and district heating are all subject to a wide-ranging energy tax in the Netherlands. Apart from energy tax, consumers pay a levy for Sustainable Energy Act (ODE) (Netherlands Enterprise Agency, 2022a). This levy is designed to fund and support schemes that promote renewables.

To enhance energy transitions, the Netherlands is modifying its tax laws. For this purpose and to aid low carbon low-carbon heating choices (including more effective heating systems such as heat pumps) and on the other hand motivate consumers, the government has the plan for imposing higher taxes on natural gas and lower taxes on electricity. The Netherlands strategy in this regard is to increase taxation of natural gas by up to 43% by 2026 (relative to 2019 levels) to assist the switch (IEA, 2020). Looking at the Britain’s plans for its energy policy, it is seen that the country is investing in the same strategy. Shifting levies from electricity to gas is also within the UK's heat pump strategies. The aim is eventually to be able to operate heat pumps cheaper than gas boilers without requiring grants (Ambrose, 2023).

Another measure to encourage end users to invest in sustainable heating methods, including heat pump installations, is the provision of financial incentives. This is aimed at making such investments more affordable and attractive to a wider range of residents through loans or subsidies. The idea is to recover part of the upfront costs of installations and lower the financial burden on individuals who wish to install heat pumps. Decreasing the interest rate on these loans as well as allocating more funds to the subsidy program may further incentivize individuals to pursue heat pump installations.

When considering the adoption of heat pumps, there is also a need to offer flexibility services to encourage the consumers (IEA, 2020). Policy makers can enhance this approach while planning to consider consumers' choice. In order to improve this flexibility regarding heat pump systems without affecting the in-home comfort of occupants, it is necessary to make some adaptations to heat pumps. An adaptation may include using a non-electric system as a backup option for the periods that heat pump is off. An option to increase this flexibility is hybrid heat pump. For instance, the Dutch government has suggested making hybrid heat pumps as the default heating system for new buildings being constructed (Netherlands Enterprise Agency, 2022b).

Seeking the targets of increasing positive attitudes of residents towards heat pumps to ultimately enhance the plan for transitioning away from natural gas, four scenarios are designated based on the possible abovementioned options, aiming at facilitating the process. Each scenario aims to show the possible changes in the system after altering one or more variables (What-If scenario). To this end, research and innovation is placed at the core of all scenarios with an emphasis on advancing the technology of heat pumps, reducing the noise, as well as improving the expertise and skilled human capital in the field.

Table 5 summarizes the four scenarios, each one designed to explore different aspects discussed above.

Table 5: Overview of the scenarios

Scenario number	Scenario Name	Objective	Concepts Tweaked (Inputs)
1	Hybrid tech. Scenario	Focus on research and innovation for advancements in hybrid heat pump technology	Research & Innovation, Hybrid tech.
2	Incentives Scenario	Emphasis on incentives to reduce upfront cost concerns	Research & Innovation, Incentives
3	Taxation Scenario	Shift focus to operating costs (energy bills)	Research & Innovation, Energy levies adjustment
4	Passive Heating Scenario	Integration of passive heating techniques, alongside energy levies adjustment	Research & Innovation, Energy levies adjustment, Passive heating

4.4.1. Hybrid tech. Scenario

The Hybrid tech. Scenario serves as the foundation for the analysis, placing research and innovation at its core. It also focuses on driving advancements in hybrid heat pump technology. This scenario is designated to seek if the expertise and skilled human capital is improved and the technology advancement results in "quieter, smarter, and lower cost price" heat pump under the Netherlands' plan of realigning the energy research and innovation (RD&D) for heat pumps and the increased availability of hybrid heat pumps to provide consumers with greater choice and flexibility, what outcomes it brings within in the system.

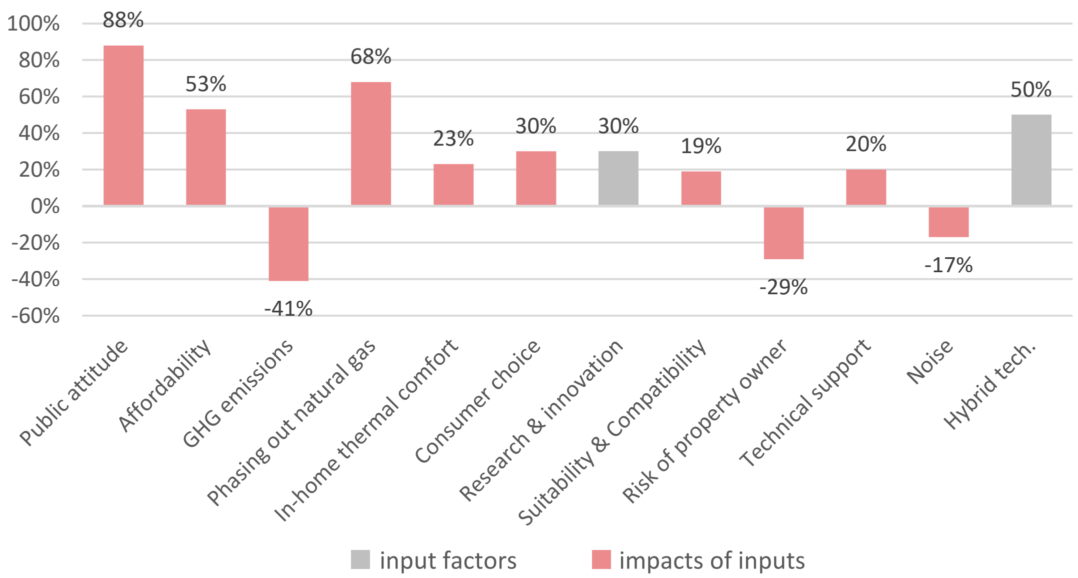

Figure 23: Output of Hybrid tech. Scenario

In this scenario, two scenario inputs consist of increasing research and innovation by 30% and increasing advancements in hybrid heat pumps by 50% (IF-input). As shown in Figure 23, the inputs of Scenario One resulted in 88% increase in public attitude and an increase of 68% in phasing out of natural gas (input factors shown in grey and impacts of inputs shown in pink). These results (THEN-outcomes) align with the preferred states mentioned before. Also, there are additional outcomes which are a 53% improvement in affordability, increasing the flexibility and consumer choice by 30%, increasing in-home thermal comfort by 23%, and increasing the technical support as a result of improved skilled human capital by 20%. The positive outcomes suggest that research and innovation, along with increased flexibility and consumer choice through hybrid heat pumps, can lead to a higher positive attitude by residents.

The Hybrid tech. Scenario, which emphasizes research and innovation in hybrid heat pump technology, indicates a positive acceptance outcome. The increased expertise and technological advancement lead to a significant increase in public attitude towards heat pumps and phasing out of natural gas. The improved affordability, flexibility and consumer choice, in-home thermal comfort, and technical support indicate the positive impact of innovation and advanced hybrid heat pumps on residents' attitudes. This scenario aligns with the survey results, which indicated that financial considerations were important for residents, and suggests that investing in technological advancements and skilled human capital can result in a positive attitude towards heat pumps. In this sense, policymaker should focus on supporting research and innovation in hybrid heat pump technology to accelerate acceptance.

4.4.2. Incentives Scenario

Similar to the first scenario, research and innovation remain central, but in the Incentives Scenario, the emphasis shifts towards incentives such as subsidies and grants with the idea of reducing upfront cost concerns. The scenario considers decreasing the interest rate on loans, allocating additional funds to the subsidy program, as well as facilitating access to these incentives. By doing so, the scenario explores the potential outcomes on the whole system.

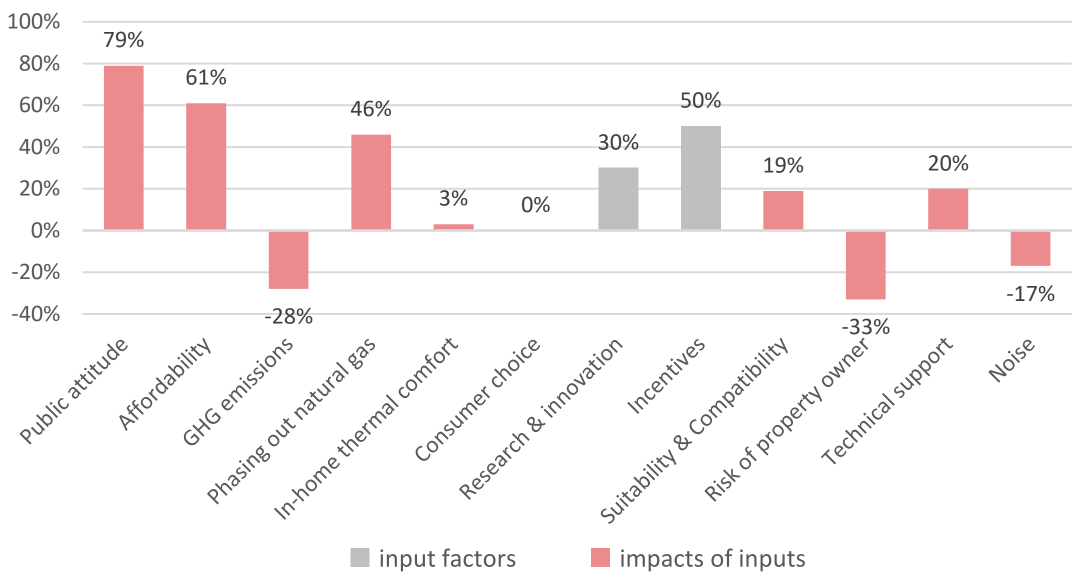

Figure 24: Output of Incentives Scenario

In the Incentives Scenario as discussed, the scenario inputs were adjusted with a focus on incentivizing. The scenario inputs consist of increasing research and innovation by 30% same as Scenario One and increasing the incentives by 50%. As shown in Figure 24, Scenario Two's results (THEN-outcomes) are slightly different. For the preferred state component, the public attitude was increased by 79% which is relatively lower compared to Scenario One. The outcomes showed higher improvements in affordability (61%). The additional outcomes are increasing phasing out of natural gas by 46%, increasing the technical support by 20%, and increasing in-home thermal comfort by 3%.

In the Incentives Scenario, while research and innovation remain important, the emphasis on financial incentives leads to a lower increase in public attitude (79%) compared to the Hybrid tech. Scenario. However, affordability shows a higher improvement (61%), indicating the potential of financial support to positively influence residents' perceptions and could be a solution to upfront cost concerns, which was shown in the survey results.

Incentives Scenario focuses on incentivizing the adoption of heat pumps by reducing upfront cost concerns through subsidies and grants. Looking more thoroughly at the simulation results, while the scenario shows positive outcomes in terms of public attitude and affordability, there is a lower increase in public attitude compared to Hybrid tech. Scenario. It indicates that incentives alone may not be sufficient to drive significant changes in public attitudes. A message to the policymaker could be combining incentives with other measures, such as research and innovation and hybrid technology of heat pumps.

4.4.3. Taxation Scenario

In scenario three, research and innovation continue to remain central, but the focus shifts towards operating costs, particularly energy bills, with the objective of running heat pumps at a lower cost compared to prevailing gas-fired heating systems. This scenario aligns with the strategy of the Dutch government to shift energy levies from electricity to gas, aiming to make heat pumps more attractive in comparison to traditional gas heating systems, without relying on grants or loans. The scenario explores the potential outcomes of implementing this strategy, which involves modifying energy levies as a means of increasing the appeal and affordability of heat pumps.

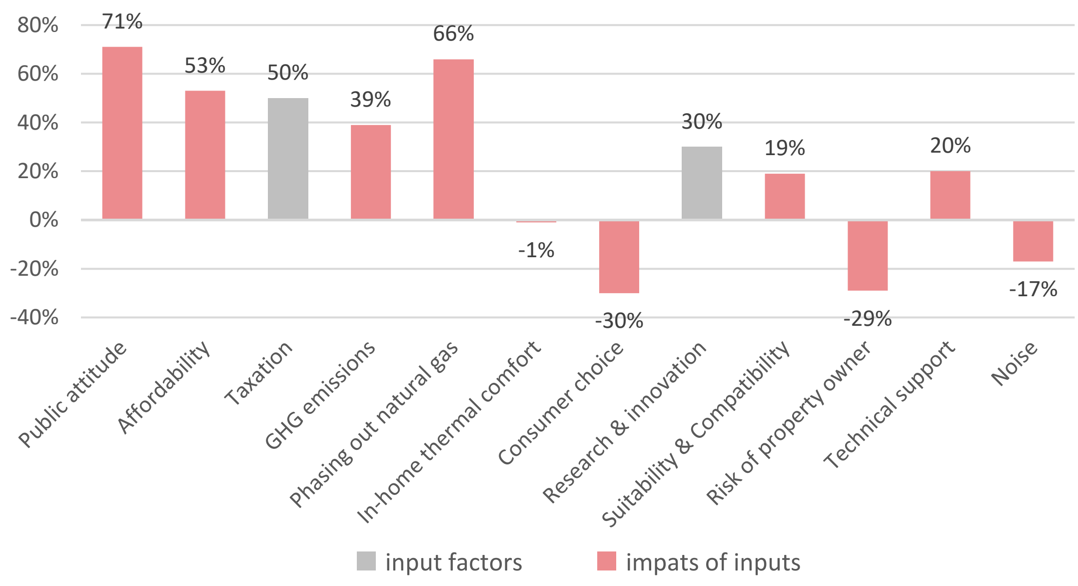

Figure 25: Output of Taxation Scenario

In the Taxation Scenario, the input of increased incentives replaced with increasing the taxation adjustments by 50%. The other scenario input of increasing research and innovation variable was kept the same with a 30% increase. As depicted in Figure 25, the results (THEN-outcomes) of Scenario Three diverged from those of the second scenario. The public attitude exhibited a 71% increase, and affordability showed a 53% increase, both of which were comparatively lower than the corresponding increases observed in Incentives Scenario. On the contrary, the phasing out of natural gas showed an increase of 66% in Scenario Three, surpassing the corresponding outcome of Scenario Two. However, in-home thermal comfort and consumer choice are marginally affected in Scenario Three with a decrease of 1% and 30%, respectively.

The Taxation Scenario targets operating costs and energy bills by modifying energy levies. This scenario supports the government's strategy of shifting energy levies to make heat pumps more appealing. By adjusting energy levies to make heat pumps more attractive in comparison to traditional gas heating systems, policymaker can encourage residents to consider heat pumps as a heating option. However, outcomes of this scenario show a slight decrease in in-home thermal comfort and consumer choice. This suggests that policymaker should carefully balance energy cost savings with residents' comfort and flexibility preferences.

4.4.4. Passive Heating Scenario

Building upon scenario three, scenario four introduces the integration of passive heating techniques (e.g., insulation of walls and windows) as a supportive measure. As mentioned earlier, passive heating techniques have been proven to deliver substantial energy savings (Dwell, 2017; the Australian Government, 2020; Tungnung et al., 2023). They could also act as a barrier to environmental noise, which can complement heat pumps' noise reduction efforts. The objective of this scenario is to explore the combined effects of implementing passive heating techniques alongside the financial measure of adjusting energy levies on the system, including public attitudes towards heat pumps.

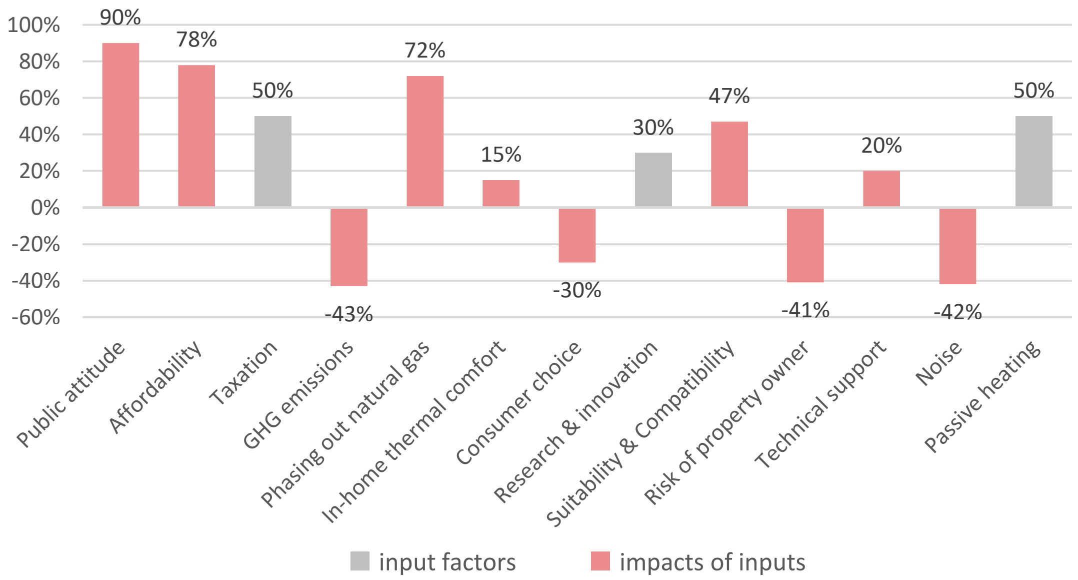

Figure 26: Output of Passive Heating Scenario

In Scenario Four, the input of passive heating techniques was increased by 50% as a supportive measure, in addition to the previous conditions of Scenario Three, which involved a 50% increase in levy adjustments and a 30% increase in research and innovation. The reason for increasing the passive heating techniques by 50% was to maintain a balance between achieving energy savings and the additional financial cost for residents. As depicted in Figure 26, the results (THEN-outcomes) of Scenario Four show a significant improvement in public attitude (90%) and also in affordability (78%). In addition, there is a more favorable outcome in terms of phasing out of natural gas, with an increase of 72%, and a positive effect on noise reduction, with a 42% improvement. Furthermore, compared to the Taxation Scenario outcomes, the impact on in-home thermal comfort is mitigated and shows a 15% increase.

As said, the Passive Heating Scenario incorporates passive heating techniques alongside energy levies adjustments. This combination leads to the most favorable outcomes, with significant improvements in public attitude, affordability, and phasing out of natural gas. This scenario communicates a "balanced acceptance world," where both financial incentives and supportive measures are combined to achieve successful energy transition and greater public acceptance of heat pumps.

4.4.5. Summary of scenarios

The scenario-based analysis aimed to assess the effects of alternative scenarios on the adoption of heat pumps and the transition away from natural gas. Four scenarios were designed based on different variables to find the potential outcomes of different policy/measure/action options with reference to the preferred state components. Figure 27 illustrates the comparative results of the four scenarios.

Scenario One focused on advancing hybrid heat pump technology through increased research and innovation. As illustrated in Figure 27, the outcome of the first scenario showed a significant increase in public attitude (88%) and there were positive outcomes in terms of flexibility, consumer choice, in-home thermal comfort, and technical support. When evaluating public attitude, it was observed that the technological input of hybrid heat pumps resulted in a more positive attitude compared to solely offering financial measures, as assessed in Scenarios Two and Three.

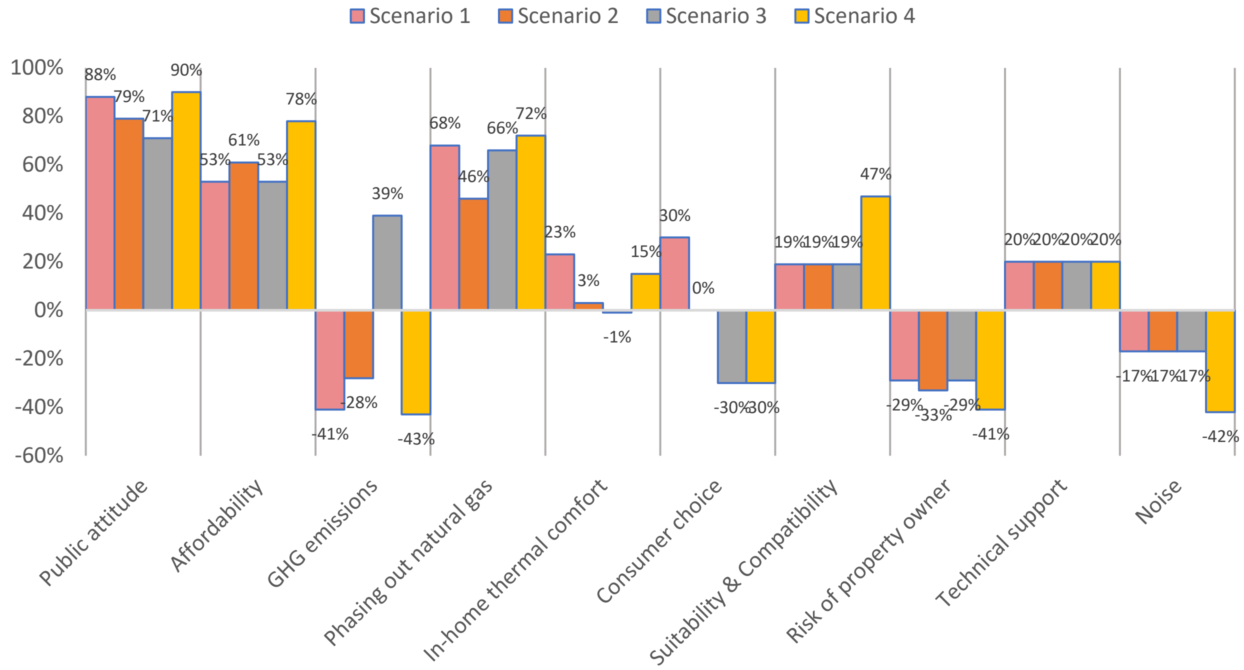

Figure 27: Comparison of outcomes across four scenarios

As said, Scenarios Two and Three focused on financial policy measures, where the emphasis in Scenario Two was on incentivizing the adoption of heat pumps, while Scenario Three explored the effects of adjusting energy levies to make heat pumps more attractive in terms of operating costs compared to gas-fired heating systems without relying on grants or loans. The outcomes of energy levies adjustment scenario showed less attractiveness to the public (public attitude) and a lower improvement in affordability compared to the scenario of increased incentives. Additionally, it resulted in decreases in flexibility and consumer choice. However, it did result in a higher rate of phasing out of natural gas.

Then in Scenario Four, the effects of another technological action, (i.e., passive heating) as a supporting measure to the financial measure was examined. All scenarios' results were, in fact favoring the preferred state with their advantages. However, scenario four demonstrated the most favorable outcomes, with a significant increase in public attitude (90%) and affordability (78%). There was a notable improvement in noise reduction too. Additionally, in-home thermal comfort showed a substantial increase of 15% compared to Scenario Three.

The conducted scenario-based analysis in this study has provided insights into various policy options to enhance the acceptance of heat pumps. In constructing an optimum acceptance policy world where the positive outcomes of the scenarios are combined to achieve optimum acceptability, a two-fold strategy could be considered, with the idea of addressing both short-term and long-term goals.

For the short term, the Hybrid tech. Scenario offers a clear solution. By prioritizing research and innovation in hybrid heat pump technology, this approach not only improves public attitude but also addresses affordability, flexibility, and consumer choice. This strategy also aligns with the resident survey's emphasis on affordability. However, recognizing the importance of financial incentives, the insights from the Incentives Scenario should be incorporated as well. By providing subsidies, grants, and reducing the upfront cost concerns, residents' acceptance could be further improved. This approach recognizes the importance of technology innovation, but also understands that financial barriers can discourage adoption. Therefore, financial incentives become valuable for increasing the acceptance among the end users.

On the other hand, for sustainable long-term success, a combination of the Passive Heating Scenario and the Taxation Scenario seems powerful. This combined approach focuses on two key aspects derived from the simulation outcomes: energy cost reduction and enhanced comfort. By adjusting energy levies and integrating passive heating techniques, the policy world reduces operating costs, making heat pumps more cost-effective compared to gas-fired systems. Simultaneously, the inclusion of passive heating techniques ensures greater energy efficiency and noise reduction. Although passive heating can be a solution for the short-term strategy too (by providing insulation for existing buildings), it could be further followed by integrating "Passive design" during the architectural design phase for new buildings. However, as a long-term endeavor, this approach requires sustained commitment and careful financial planning to drive lasting transformation.

4.4.6. Limitations

This study has a number of limitations that need to be acknowledged. First of all, due to the qualitative nature of this research, it is important to note that the findings may be influenced by the subjective perspectives of the experts interviewed. However, to improve the reliability and validity of the results, it was attempted to ensure diversity in the selection of experts interviewed with a range of techno-economic backgrounds. Secondly, despite the high response rate of the public survey, time constraints of the research plan limited the ability to reach out to a larger number of residents. As a result, the generalizability of the findings may have been somewhat limited. Thirdly, in order to lower potential refusals or survey abandonment by participants, the surveys were designed to gather data on the most relevant factors utilized in the developed FCM. While a more extensive set of questions could have provided a more comprehensive understanding of the system and more connections in the FCM map, due to the mentioned limitation, only the most relevant factors were included in the surveys. It should be noted that other methodologies, both quantitative and qualitative, could also support the FCM approach. Quantitative methods like statistical analysis could provide more insight into the relationships between variables. Moreover, qualitative techniques, such as in-depth interviews or focus groups, could also be used to further explain the fine distinctions between residents' attitudes and perceptions. The special thing about the FCM method used in this study is that it helps to see how everything is connected in a big picture, making it feasible to model the socio-technical complexity that is present in the heat pump adoption system.

5. Conclusions and recommendations

In this research, the adoption of heat pumps and factors contributing this adoption by residents for the mission of energy transition and phasing out of natural gas in the Netherlands was analyzed thereby, aiming to answer the overarching research question “How can technology acceptance accelerate the adoption of heat pump systems in urban NL?” To answer that question, two sub-questions were formulated: The first sub-question concerning key factors affecting the decisions of urban households to adopt heat pumps, was answered through the data acquired from the interview and surveys and according to the theoretical framework of TAM. And the second sub-question concerning techno-economic changes to improve residents ’attitudes towards heat pumps was examined and answered through the scenario analysis (what-if scenarios).

In the course of this thesis, following the background research and identifying the main concepts during the initial key-informant interview, a public survey was conducted from the local population of the city of Leeuwarden, which was a representative case of urban NL, to gather residents’ perceptions, concerns, preferences, but also their experiences about heat pumps to obtain a comprehensive understanding of the factors influencing their attitudes towards heat pump adoption. As expected, gas fired boilers were the most prevalent heating system among the surveyed residents, which was consistent with the overall installations situation in the country. During the survey it was found that financial considerations had the highest priority for the residents when it comes to choosing heat pumps as the primary heating system. It was also observed that some residents had no prior knowledge about this technology and also some residents did not know about the heating system they currently had. Though this lack of knowledge could be due to various reasons, such as limited involvement in managing heating systems, it underscores the importance of increasing awareness. So, a possible recommendation in this regard could be providing more education about heating systems, especially alternative options such as heat pumps. By addressing the lack of knowledge and promoting the benefits of energy-efficient and environmentally friendly heating solutions, it could encourage greater adoption of sustainable heating technologies.

Other than gathering public attitudes, experts’ opinions were also captured to evaluate the influence of each concept on the other concepts, investigating both direct and indirect impacts through the interlinkages in the system. This survey covered different concepts of the system, including social, environmental, technological, and economic aspects. The findings of this survey contributed to determine the strength of the causal relationships and interlinkages between different concepts related to heat pump adoption. Interestingly, the highest confidence value was associated with the impact of a technological concept on the affordability factor which was “Passive heating techniques”, surpassing economic measures.

The findings of these field surveys were then used as the input data for FCM mapping. The causalities of the FCM were derived by defuzzification of survey responses to determine the degree of causality between different concepts. The fuzzy cognitive map-based modeling enabled the qualitative comparison of concepts with different nature in the system. Then, in order to analyze the data, a scenario-based analysis was performed. This analysis aimed at assessing the effects of alternative scenarios on the adoption of heat pumps and the transitioning away from natural gas. To this end, four different scenarios were designed and tested to find the potential outcomes of different policy/measure/action options with reference to the preferred state components. By developing these scenarios, the Netherlands’ energy transition goals to support the transition from natural gas to alternative low-carbon heating options were followed through techno-economic changes that would help accelerate the process. The outcomes of the four scenarios showed that each scenario has some advantages. Hybrid tech. scenario could add flexibility to the system and provide more consumer choices. The scenarios that incorporated incentives (scenario two), or adjustments in energy levies (scenario three), showed positive outcomes but had some trade-offs in terms of in-home thermal comfort and consumer choice and flexibility. The integration of passive heating techniques in scenario four resulted in the most favorable outcomes. In constructing an optimum acceptance policy world to achieve optimum acceptability, a two-fold strategy was proposed, with the idea of addressing both short-term and long-term goals. For the short term, Hybrid tech. Scenario was offered as a clear solution in combination with research and innovation in the technology along with providing subsidies, grants, and reducing the upfront cost concerns to improve public attitude but also to improve the affordability, flexibility, and consumer choice. For sustainable, long-term success, integrating passive heating techniques and adjusted taxation was proposed to also offer energy cost reduction, comfort enhancement, as well as noise reduction. These scenarios collectively underline the importance of complementary measures to enhance the overall effectiveness of heat pump adoption strategies. Additionally, it highlights the potential synergies between financial measures and supportive strategies like passive heating techniques to achieve a well-rounded heating system.

The theoretical contribution of this research lies in the application of the Technology Acceptance Model (TAM) on a case within the context of energy transition through heat pumps. Through an experimental analysis, this study adds to the existing body of TAM literature by implying how TAM dynamics vary along several dimensions. Moreover, it highlights the potential of the TAM as a valuable tool for policy evaluation. And lastly, this case study makes a further contribution by extending the earlier studies in the field of sustainable solutions for built environments, focusing on heat pumps, by offering insights into the broader technology acceptance of heat pumps in residential areas of the Netherlands with an experimental analysis approach to predict the possibility of the future through techno-economic changes in the dynamics of the system.

Based on the findings and analysis conducted in this research, some recommendations could also be proposed to further facilitate the process and promote the wider acceptance of heat pumps, as follows:

Recommendations

1- In line with the Hybrid tech. Scenario's emphasis on research and innovation, leveraging information campaigns could play an important role. The Hybrid tech. scenario with emphasis on research and innovation and its positive outcomes on public attitude and technical support underscore the importance of educating consumers. Accordingly, besides financial policy measures, information campaigns can be used in order to raise the public awareness about heat pumps and also to dispel their misconceptions. By providing accurate information, but also the most recent technological improvements, these campaigns can educate consumers about the benefits of heat pump systems, but also the most recent technological improvements of the new systems. Additionally, promoting community-level dialogue can help build trust in the system and share knowledge with households thinking about switching to heat pumps.

2- The Incentives Scenario showed the effectiveness of financial measures, with affordability being a primary concern for residents. To enhance this, one-stop shops could be a reinforcement. Establishing one-stop shops or comparer tools could assist consumers in making choices when choosing their heating systems. These One-stop shops can provide advantageous services, including cost assessment, skilled installers, financing options, and subsidy applications for heat pumps. These resources could also be valuable when consumers urgently need to replace a broken heating system and may overlook alternative options, such as heat pumps.

3- Providing reliable third-party energy audits (even free, through efficiency programs) could be a guidance for consumers when considering heat pump installations. These audits provide trustworthy information that can help consumers make choices in terms of the energy efficiency and suitability of heat pumps. This can be very helpful, especially when the taxation adjustments are implemented, to help consumers in their decision making when considering heat pumps.

4- The need to increase in technical support, which was part of scenario results, communicates the need for skilled installers of heat pumps. To address the current shortage of heat pump installers, specific training that are required for heat pumps could be incorporated into the existing qualification courses for HVAC technicians, electricians, and plumbers. By using this existing pool of skilled professionals, we can utilize the potential of this human capital source to meet the demand for skilled installers.

5- In addition to supporting programs for building insulation and retrofitting, providing education and training to architects regarding heat distribution systems and the concept of "Passive design" can make new buildings well-suited for heat pump installations and minimize energy consumption costs. This proactive approach ensures that new constructions are optimized for heat pump efficiency. The Passive Heating Scenario's integration of passive heating techniques aligns well with this solution, as this scenario's positive outcomes in affordability, public attitude, and noise reduction confirms the value of passive design in this regard.

6- To address landlord challenges, alternative business models could be implemented to tackle the split incentives between landlord and tenants. Alternative business models, particularly energy performance contracts (EPC), in which the heat pump remains the property of the service company, and the occupant pays for the energy bill, can lower the risk to property owners regarding the investment in adopting the heat pump. This idea is in line with the concept of reducing risk of property owners about the investment in heat pumps, suggested in discussed scenarios with the goal of improving the public attitudes towards heat pumps.

Future research:

This research aimed to assess different parameters that could play a role in the public attitudes towards heat pumps and examining techno-economic changes that could enhance public perceptions. The strategy suggested in this study might be tested in other situations. Thereby, further research could be conducted on other aspects, such as the integration of heat pumps with smart grid technologies. Moreover, exploring the opportunities for collaboration and knowledge-sharing between stakeholders involved in the heat pump ecosystem, such as manufacturers, installers, policymakers, and consumers could be further studied to investigate how it could and address common challenges towards heat pump adoption.

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Appendix

1- Consent form

CONSENT FORM TO TAKE PART IN A RESEARCH INTERVIEW
Research Topic: Adoption Heat Pumps in the Netherlands

Taking part in the study for THE RESEARCHER and RESEARCHER'S SUPERVISOR at the University of Twente, The Netherlands:

I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.

I understand that taking part in the study involves answering questions from a semi-structured questionnaire and note-taking by the researcher.

I understand that in any report on the results of the research, my identity will remain anonymous if prefer to be so.

I understand that I am entitled to access the information I have provided after the interview, and I have the right to request modification, clarification, or changes where applicable.

I understand that I am free to contact the researcher for further clarification and information.

Use of the information in the study
I understand that the information I provide will be treated confidentially and used strictly for research purpose/master thesis report writing.

2- Key Informant interview questions

Purpose: main challenges that consumers face when considering the purchase of heat pumps

Questions:

1- What are the benefits of using heat pumps for consumers?

2- What are the main upfront costs of heat pumps?

3- How are the maintenance costs of heat pumps compared to the gas boilers?

4- How does using heat pumps affect the energy bills compared to the gas boilers?

5- Technical or logistical barriers that can prevent the widespread adoption of heat pumps?

6- From the consumer side, do they need to do anything to prepare their dwelling prior to installation?

3- Residents’ survey (English)

Leeuwarden Residents' Attitudes and Concerns towards Heat Pumps

Thank you for participating in this questionnaire. This survey is part of my master’s thesis in the field of environmental and energy management. The purpose of this survey is to gather insights into the attitudes and concerns of Leeuwarden residents regarding heat pumps (please see next paragraph for more information about heat pumps). The aim is to help policy makers decide how they can promote the uptake of heat pumps. So, if you are over 18 and a resident of Leeuwarden, your participation is appreciated.

A brief overview of what a heat pump is: A heat pump is an energy-efficient technology that can provide heating for residential buildings. A heat pump extracts heat from the outside your home and transfers it inside, providing warmth during colder months.

(Outdoor unit of a typical heat pump)

Heat pumps have gained popularity as a sustainable alternative to traditional heating systems.

Ethical Consideration: Your responses to this questionnaire will help us understand your perspective and concerns regarding heat pumps. The questionnaire does start by asking for some personal details, such as age. However, I will stress that these will not be in any way linked to your name. Your participation is entirely anonymous.

1. Have you read the consent form provided and are you willing to participate in this questionnaire?

- Yes
- No (Note: Please select "Yes" to continue with the questionnaire.)

2. Gender:

- Male
- Female
- Other
- Prefer not to say

3. Age Range:

- 18-30 years old
- 31-45 years old
- 46-65 years old
- More than 65

4. What is your work occupation?

- Employed
- Unemployed
- Student
- Retired

5. Annual Income (in euros):

- Less than 20,000
- 20,000-40,000

- 40,000-60,000
- 60,000-80,000
- More than 80,000
- Prefer not to say

6. What is your current residence situation?

- Own apartment
- Rental apartment
- Own house
- Rental house

7. How many people are resident at your home?

- 1
- 2-4
- More than 4

8. Before this survey, did you know about heat pumps?

- Yes
- No

9. What is your current system for heating your home?

- Gas boiler
- Electric heater
- District heating
- Heat pump
- Other (please specify) ______

10. How important is it for you to have the freedom to choose the heating system for your living place?

- Not at all important
- Slightly important
- Moderately important
- Very important
- Extremely important

11. If you were to have a heat pump or have already installed one, what would be the main reason for this decision?

- Saving on energy bills
- Contributing to sustainability and reducing environmental impact
- Reducing the use of natural resources (such as natural gas)
- Financial incentives or funds available for heat pumps
- Other (please specify)

12. This question aims to understand how the following factors influence your decision to adopt or retain a heat pump at your living place. To gain a strength of feeling about a factor, can you indicate by putting a cross on a number of stars in which 1 = not at all, 2 = slightly, 3 = moderately, 4 = very, and 5 = extremely.

In-home thermal comfort: ☆ ☆ ☆ ☆ ☆

Contributing to reducing greenhouse gas emissions: ☆ ☆ ☆ ☆ ☆

Owners only: Cost of purchasing & installation: ☆ ☆ ☆ ☆ ☆

Owners only: How long later I recoup my investment: ☆ ☆ ☆ ☆ ☆

Energy bills: ☆ ☆ ☆ ☆ ☆

Reducing use of natural gas: ☆☆☆☆☆

Consultation and skilled workers for installation & maintenance: ☆☆☆☆☆

Noise pollution: ☆☆☆☆☆

13. To what extent is the available outdoor space for installing the heat pump unit a concern for you? (a typical photo provided in the introduction)

- Not at all important
- Slightly important
- Moderately important
- Very important
- Extremely important

14. After reading all the information above, would you like to adopt or retain a heat pump at your house?

- Yes
- No

4- Experts' survey

Energy Transition in Urban NL through Heat Pumps: A Fuzzy Cognitive Map-Based Modeling

Thank you for participating in this survey, which intends to investigate the factors influencing the uptake of heat pumps by residents in urban NL. In this research, I have chosen Leeuwarden as a case study and to gather insights into the attitudes and concerns of residents, I conducted a survey targeting the local population. The survey included a range of questions covering various aspects, such as awareness of heat pumps, financial considerations, environmental concerns, and other relevant factors identified from the Technology Acceptance Model (TAM).

By exploring the concepts related to heat pump adoption, I aim to identify the key factors influencing residents' decision-making process, but also assist policymakers to develop effective strategies and initiatives to promote the wider acceptance of heat pumps.

Purpose of this Survey: Through this survey, I aim to capture your opinions on the causal relationships between different concepts related to heat pump adoption, exploring both direct and indirect influences through a Fuzzy Cognitive Map (FCM). FCM is a tool that represents the interconnections of the dynamics of every complex system. **This questionnaire seeks your expert evaluation of the strength of relationships between concepts. Your rating score in each question will determine the significance and relevance of these relationships.**

The survey includes 16 technical questions about heat pumps, which will be scored on a scale of 1 to 5 and expected to take approximately 10-12 minutes.

Consent form: This survey is fully voluntary and anonymous, and you may withdraw from the survey at any time. All responses provided in this survey will be treated with the utmost confidentiality. The information gathered will be used solely for academic purposes. Feel free to contact the researcher if you have any questions about the questionnaire in advance. The sender's email is s.rafiei@student.utwente.nl.

1. Have you read the consent form provided and are you willing to participate in this questionnaire?

○ Yes

2. What is your profession/ expertise?

○ Energy Transition Specialist

○ Environmental Specialist

○ Economic Analyst

○ Social Scientist/Sociologist

- Technical Engineer
- Energy Policy Expert
- Other (please specify)

3. What is your company specialization?

In each of the following statements please indicate to what extent are you confident in the statement by selecting one of the choices provided: Not at all confident, Slightly confident, Moderately confident, Very confident, Extremely confident.

4. In terms of affordability of heat pumps, it could be enhanced via:

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

- Hybrid heat pumps
- Grants for purchasing heat pumps
- Adjusting levies: Levy shift from electricity bills to gas bills
- Funding in energy research & innovation
- Passive heating techniques such as insulating walls and windows to save on energy bills

5. "Adjusting levies, specifically lowering the tax on electricity and increasing it on gas, can facilitate the phase-out of natural gas."

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

6. "Referring to question no.5, adjustment in levies may reduce the freedom of choice of heating system for consumers."

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

7. "Hybrid heat pumps can give the consumers freedom of choice in the heating system for their homes."

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

8. Funding in energy research & innovation programs can address the challenges stated below:

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

- Reducing the noise generated by heat pumps during the operation
- Improving technical support and energy consultations for residents through training and education

9. "Passive heating techniques, specifically insulating walls and windows, could also provide a barrier to noise of heat pumps."

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

10. "Transition away from natural gas in the heating sector can negatively impact the in-home thermal comfort of residents."

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

11. "Hybrid heat pumps can increase the in-home thermal comfort perceived by the residents."

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

12. "Suitability of building contributes to the sense of thermal in-home comfort."

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

13. Suitability and compatibility of buildings could be improved via:

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

- Passive heating techniques to make homes more suitable
- Energy research & innovation, making heat pumps more compatible

14. "Hybrid heat pumps can play role in phasing out of natural gas."

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

15. "Transition away from natural gas in the heating sector contributes to the reduction of greenhouse gas (GHG) emissions."

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

16. "If the social and residents' attitudes towards heat pumps increases, it would contribute to the successful phase-out of natural gas."

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

17. "Uptake of heat pumps may pose a risk for property owners, also in cases of split incentive between the owner and tenant."

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

18. "Price of heat pumps is a source of risk for property owners."

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

And the last question:

19. "Referring to question no. 18, alternative business models, particularly energy performance contracts (EPC), can lower the risk to property owners and improve affordability."

Note: in these contracts, the heat pump is the property of the service company, and the occupant pays for the energy bill.

Not at all	Slightly	Moderately	Very	Extremely
○	○	○	○	○

5- Professions and areas of expertise of surveyed experts

- Environmental Specialist
- Economic Analyst
- Energy Policy Expert
- Energy Transition Specialist