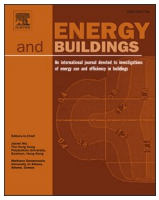
Energy & Buildings 338 (2025) 115725

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb



'Try this and see if it works for you': A new perspective on household improvisation and responses from heat pump supply-side actors☆

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ARTICLE INFO

Keywords:
Value chain innovation
Socio-technical innovation
Stakeholders
Occupant behavior
Heat pumps
Housing renovations
Energy transition
Improvisation

ABSTRACT

This paper innovates in the relationship between sustainable technology suppliers and users, using the example of heat pumps. Heat pumps are necessary for energy transitions in Europe. However, in everyday life in households, heat pumps are often not used as the technology developers intended. This discrepancy presents a challenge for heat pump supply-side actors such as manufacturers and resellers. This paper first presents a design perspective on user improvisation and highlights its value for innovation. We synthesized the perspective in a sensitizing video. We then employed this video to engage with nine supply-side professionals in the Dutch heat pump value network and conducted semi-structured interviews with them to understand their responses to improvisation. We categorized their responses and identified the factors influencing the choice of response. We identify ten different responses and nine motivating factors. We then interpret the responses in the light of our design perspective on user improvisation to highlight areas for socio-technical innovation in the relationship between the heat pump supply and use sides. This innovation can support heat pump uptake and satisfaction and thus improve the quality and rate of renovations.

1. Introduction

The building sector is responsible for approximately 36 % of the greenhouse gas emissions in the EU (European [1]. Therefore, the energy performance of the European housing stock is an important target for low-carbon transitions. Yet, as it stands, the rate and depth of renovations to increase this energy performance lags in the required pace to reach climate goals. Heat pumps are important products within these renovations, specifically for the Dutch housing stock [2]. Recent studies have started to investigate how heat pumps are taken up in everyday practices of residents and found that the use of heat pumps (termed 'occupant behavior') is often not as expected [3–5]. This discrepancy (between intended and unintended use) has been considered a contributing factor to the performance gap; a gap between predicted and actual energy use in renovated buildings [6,7]. This discrepancy also presents a challenge for the heat pump value chain (or 'supply side'), such as manufacturers, wholesalers and service partners, as it leads to uncertainty about actual energy savings. The uncertainty in turn affects the customers' willingness to invest in low carbon technologies such as heat pumps. We posit that a reason for the discrepancy between intended and unintended use is that the heat pump value chain at this moment remains largely disconnected from the everyday use of heat pumps post-installation (on the 'demand side). This prevents the value chain from learning from use and addressing unintended use. Connecting the heat pump value chain better with heat pump use can potentially speed up learning and improve the quality and rate of renovations.

This study explores the connection between the heat pump value chain and heat pump use. We study how actors in the heat pump value chain interact with use, particularly unintended use. To clarify, this study is not primarily about the technological aspects of heat pumps – although we offer some implications for heat pump design choices – but about a crucial gap in the value chain and how it could be addressed with innovation in the interaction between demand- and supply side actors.

We bring a specific perspective to the investigation: a perspective informed by current design research. In this perspective, unintended use is viewed as an opportunity to adapt to and collaborate with end-users. It positions use and design in a closer relation with each other. A key term

☆ This article is part of a special issue entitled: 'Housing energy transition' published in Energy & Buildings.

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https://doi.org/10.1016/j.enbuild.2025.115725
Received 10 June 2024; Received in revised form 20 January 2025; Accepted 7 April 2025
Available online 15 April 2025

we use in this is 'improvisation', to describe the ways in which residents' practices deviate from prescribed use, and all the other types of unintended use or unexpected occupant behaviors. We use the term 'response' to refer to the ways in which professional practitioners in the heat pump value chain engage with this improvisation.

We seek to answer the following questions: How do professional practices in the supply side of heat pumps respond to improvisation? This can be further split up into the following sub-questions: 1.) What is the current diversity in responses by professional practitioners to improvisation by end-users of heat pumps? 2.) Which factors determine the choice of response for professional practitioners? Having explored these questions, we then consider how our design research perspective highlights areas for innovation in the relations between supply side and use.

Understanding professional responses to improvisation sheds light on an area that has not been explored in depth: the relation between the supply side and the use of heat pumps. This study sheds new light on connections and relations between heat pump development and use. Understanding these connections can highlight areas for improvement in this relationship and inform socio-technical innovations (innovations that integrate social and technical perspectives [8]. In this context, these innovations can enable (faster) learning by supply-side actors and other ways of productive engagements with unintended use [9]. On a larger scale, such improvements are required to ensure that the transition to heat pumps is achievable and responsive to residents' activities, socio-economically feasible, and ultimately leads to reduced energy consumption on a national level. As such, this study aims to present a holistic view of renovations and heat pumps that integrate both the renovation themselves and the use phase.

We structure this paper as follows: we first briefly discuss the Dutch heat pump transition, the relevance of heat pump use, and the current gap between the supply side and the use situation. After explaining and grounding our design research perspective in literature, we discuss our methodology. We prepared interviews with relevant professional practitioners throughout the heat pump value network in the Netherlands. In preparation for these interviews, we produced a sensitizing video that communicates our perspective and the idea of improvisation by proposing several potential responses to improvisation. This video becomes a stimulus in the latter part of each respective interview. After describing the results from the interviews in ten responses and nine determining factors, we discuss our results with reference to literature and highlight how introducing our perspective in relation to interview data, suggests socio-technical innovations connecting supply side and use.

2. Background and related work

2.1. The Dutch heat pump transition

In many European countries including the Netherlands, heat pumps are considered a key factor in improving the energy performance of housing, contributing to less energy use by, and more sustainable sources for, domestic heating [10]. This transition is motivated by European policy, which sets requirements for decarbonization to member states, as well as an interest in moving away from natural gas as an energy source due to ending exploitation of a gas field in the north of the country, and the reduction of natural gas import from Russia following the war in Ukraine. The Dutch demand for heat pumps increased significantly in 2022, but the market is still small [11]. This small market share has been explained with reference to low prices of gas, compared to electricity prices in the Netherlands (making gas-based boiler systems financially equally or more attractive) [12]. These economic motivations are also likely the explanation behind the market increase in 2022, following rising gas prices.

Current research on supporting the Dutch heat pump transition targets households as consumers doing energy-efficient renovations and acquiring technologies such as heat pumps [13–15]. Proposed policy measures typically target building standards for new buildings, provision of information, or further subsidies for energy-efficient technologies or taxes on energy carriers [16].

2.2. Critical use aspects of the Dutch heat pump transition

There is an increasing awareness that, beyond the initial purchase decision informed, for example, by gas prices, the use phase is a critical factor limiting uptake and satisfaction, as energy saving measures do not always have the intended result in terms of energy performance. However, post-occupancy evaluation of energy performance in buildings is still rare. In the field, such evaluations remain primarily concerned with quantifying aspects (indoor and outdoor temperatures, thermostat set points, etc.) as critically assessed by Chiu et al. [17]. These post-occupancy studies find that energy labels do not accurately reflect actual energy use in Dutch households [18,19], a phenomenon also described as the performance gap. Rebound effects refer to situations where efficiency improvements from technologies like heat pumps lead to unintended increases in energy consumption, partially offsetting the intended energy savings. One Norwegian study on the rebound effect found that, compared to conventional electric heating, no energy was saved by implementing air-to-air heat pumps [20]. Often, this rebound effect is explained with reference to increases in comfort expectations and changes in heating practices [21,22].

This section first highlights a number of aspects that are relevant to use. Heat pumps in the Dutch context replace gas-based boiler systems. Compared to these heating systems, heat pumps present several novelties to residents. One notable change is low-temperature heating, which performs best when the thermostat is set to a stable temperature. Heat pumps operate most effectively in well-insulated buildings with larger low-temperature heat emitters, preferably under-floor heating or convector radiators, which heat indoor air slowly and evenly, rather than quickly. This means that the temperature cannot be as spontaneously adapted, and that warmth may become less noticeable to residents. Sometimes, additional fans are placed within convectors in the rooms that move hot air through the spaces more quickly, providing thermal comfort to the occupants without the need for high supply temperatures. These fans might be automated, or require operation by residents. In a building with an air-tight insulated outer shell, consideration of building ventilation becomes increasingly important to ensure healthy indoor air quality (Balvers et al., 2008). The adequate performance of mechanical ventilation systems requires regular cleaning and exchange of air filters by users.

Another relevant feature of most heat pumps is their limited capacity to produce domestic hot water. Systems deal with this by heating the hot water slowly (often during the night) to 55 °C and storing it in a storage tank until needed. Typical storage tanks have a capacity of 100–200 L. A 2008 study in the UK found that the mean domestic hot water consumption per household is 122 L a day (Measurement of Domestic Hot Water Consumption in Dwellings, 2008). This means that user behavior in terms of domestic hot water consumption (showers, hot tap water for cleaning, etc.) is relevant in terms of how often hot water is produced, and how much of it is available by the end of the day.

Several studies discuss the use phase in which residents interact with heat pumps. The studies highlight how user behavior plays a critical role. The features mentioned above, require changes to everyday practices of residents, otherwise heat pumps do not reach their predicted performance. Earlier studies have shown that during adoption and in everyday life, heat pumps require a reconfiguration of understandings (e.g., residents need to learn how these systems work), material reconfigurations (e.g., increased insulation) and reconfiguration of routines (e.g., what clothes to wear) [3,5,12,23]. These studies highlight that the heat pump transition in the Netherlands and elsewhere suffers from a lack of alignment between intended use (heat pumps swiftly taken up in daily practices) and actual use, which prompts the reconfigurations mentioned above.

These earlier studies uncovered that unexpected use practices can also have positive effects. Nyborg [24] observed inventive uses such as Danish households' ability to modify a relay in a heat pump to shut the heat pump down completely at night. Hyysalo et al. [25] described inventions that users made to their heat pumps and other heating technologies. The users significantly improved these technologies to match their specific situation and shared their innovations through internet forums. Similarly, a recent study found that there is innovative potential in the adaptations that users make to give heat pumps a place in everyday life [5]. This experimentation and innovation has an important potential role to play in sustainability transitions, since it could provide valuable input for the heat pump value chain. [12,26].

Together, these studies highlight how the use situation of heat pumps is relevant to the supply side, both for realizing predicted energy savings and for potentially positive or inventive outcomes of everyday practices.

2.3. Some bridges connecting use to the heat pump supply side

Meanwhile, for the supply side of heat pumps, this use phase is currently mainly regarded as a challenge. In the Dutch heat pump transition, this supply side consists of heat pump manufacturers, installers, developers and implementers of monitoring and those deciding to implement heat pumps on a larger scale. For these actors it is very relevant to have correct predictions of energy consumption in the use phase as this is the informational basis on which heat pumps are sold. This information is what is used to advise installers choosing heat pump models. Such predictions determine the return on investment for their customers, but also inform decisions about which heat pump fits specific buildings and use situations. Understanding use patterns is also highly relevant to understanding how long installations will last. The use phase is also evidently relevant as the period in which complaints from end-users will appear. Such complaints might lead to extra work and failure costs, but also potentially to rejection of heat pumps by customers or a bad reputation of installations. For some actors in the supply side, the use phase is even more relevant as the current context shows the emergence of contractual binds between heat pump manufacturers, installers and end users in the form of energy performance guarantees. Breaching these can have legal and financial repercussions and might also contribute to a negative perception of heat pump technology. These factors together seem to call for developing a much better understanding of how provision (the supply side) and consumption (practices of use) interact [27].

However, in spite of calls for further enquiry of the supply chain of domestic retrofit [28] there has been little investigation of the supply side of heat pump renovations and how it interacts with the use of heat pumps. Some studies have looked at the role of installers and other so called 'intermediaries' and found that their potential influence towards energy efficient behaviors post-installation was not realized [29–31]. Other studies have looked at the hand-over process and its influence on user behavior [32], or study sales and installation [22,33] and how these practices interact with energy related everyday household practices. Another study used user centered design to understand the service of installing heat pumps in UK social housing [34].

While installers and intermediaries are thus receiving increased interest, the role of the further supply chain has received less attention in academic research. This might be in part explained by, what is traditionally considered, a rather large gap between manufacturer and end user. An important study (again from the UK) puts this in perspective [35]. The authors highlight that the operational impacts (i.e., energy consumption in the use phase) of buildings are remote from the control of manufacturers working in high-volume, mainstream markets. Manufacturers sell their product to 'merchants' (resellers), who sell to designers (or contractors and architects) who then sell to installers, who then install installations for their clients as end-users (Fig. 1.). Beyond sales, there are some links connecting the separate actors along this chain, in the form of accreditation and advice, but the length of the chain is still considerable. Manufacturers' influence on end-users is therefore generally indirect, via installers (Fig. 2).

However, Killip et al. also give several reasons why there is (or could be?) an increasingly closer connection between manufacturers and end-users. First, innovations in the sector (most notably BIM and off-site construction) alter the value network and create stronger links along the value chain. (Other studies have added performance monitoring as another innovation that creates such links [36]. Secondly, green markets require manufacturers to stand out, and to demonstrate their expertise and experience to clients. This enables innovation, specifically beyond the project level. The authors note that *"when middle actors and end-users share a value-driven commitment to reducing building environmental impacts of all kinds, the relationships can take on the quality of friendship. However, the scale of activity among the green businesses is a long way from being sufficient to meet policy goals"* [35]. Our work responds to this call for increased activity along the chain.

2.4. The focus of our study

To enquire into the value to be found in the connection between the supply side and end-use of heat pumps, our study focusses on those in the heat pump value network with the capacity for innovation. This means, as also indicated by Killip et al. [35], that we target actors working beyond single projects, who can create new links to the end user in their practices and processes. This set of innovating actors in the value network include heat pump manufacturers and resellers, but also those developing performance monitoring [36]. In addition, our earlier experiences in this field and previous work by Cauvain and Karvonen [37] revealed that social housing providers also play an important innovating role and have a large degree of agency when it comes to installing heat pumps. They make important socio-technical decisions in retrofits (relating both to their tenants and to specific heat pump features).

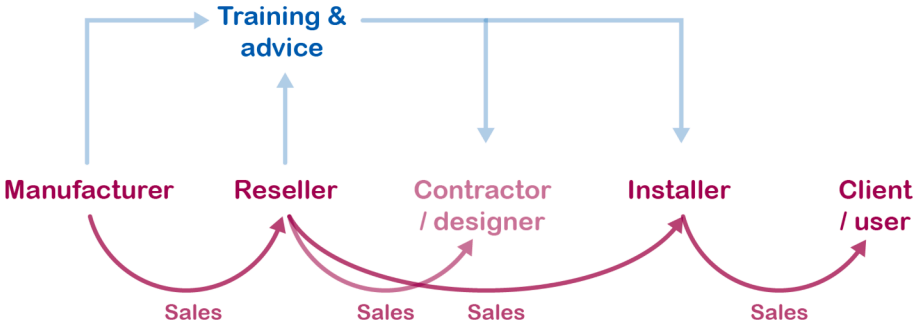


Fig. 1. Value network relationships and activities (simplified and []). adapted from [35]

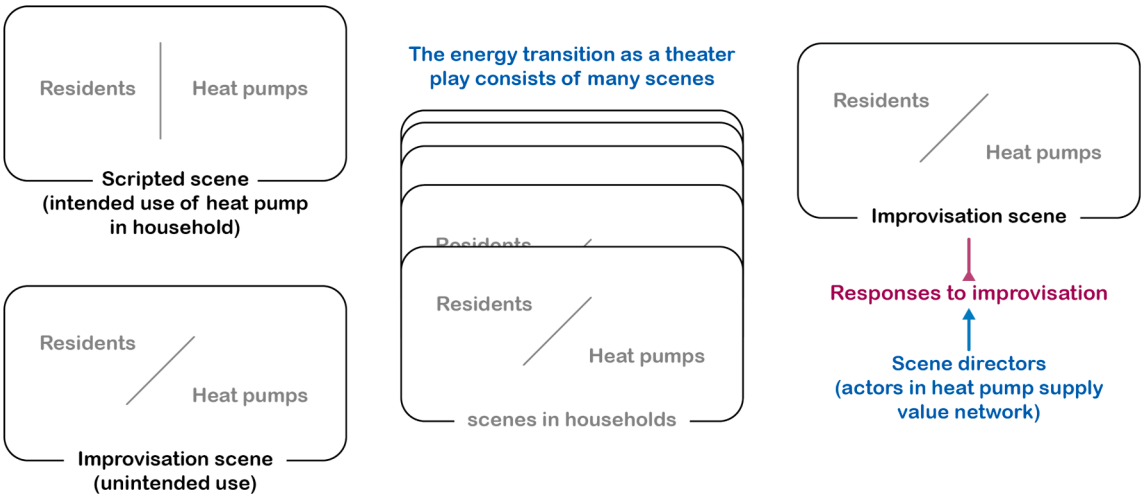


Fig. 2. A diagram explaining our performative perspective, and the focus of this study (in red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Framing unintended use through a new perspective for the supply side: Improvisation in practices and professional responses

3.1. Perspective 1: Unintended use as risk

In section 2.2 we have described how heat pumps are not always used as intended by residents, and in section 2.3 we substantiated why this unintended use is relevant to actors in the heat pump value network. Until now, in literature, this unintended use has been primarily approached as an inadequacy of prediction. Following this view, research attempts to collect more realistic data about residents (e.g., post-occupancy evaluation) and does so to correct design assumptions [38]. On the other hand, unintended use patterns have also been regarded as an inadequacy on the side of users who do not follow the instructions given to them. Research in this line investigates how residents can be better instructed or interfaces can be designed in a more transparent way [39]. Such a view evaluates unintended use as a risk to energy performance. Excesses in energy consumption and further instructions are addressed as failure costs: builders and installers incur costs and engage beyond the standard activities [40]. Such a framing was adequately captured by the provocative title of a ESRC seminar: “How people use and ‘misuse’ buildings”. In this seminar, practice theorist Elizabeth Shove argued for a critical unpacking of the notion of misuse [41].

In our particular unpacking, we propose a different view of unintended use. Drawing from ideas from design research, science and technology studies and practice theory, we suggest a *performative* understanding of unintended use. We explain our perspective below.

3.2. Perspective 2: Unintended use as improvisation

An important goal of design research is connecting the lifeworlds of end users to the development of technologies that enter those worlds [42,43]. These connections can take many forms (user studies, A/B testing, or participatory design). A key commitment in developing these connections is the appreciation of end users as skilled practitioners of their own lives [44]. End-users are not just recipients of technologies, but have an embodied know-how of the challenges and solutions they encounter in everyday life. From such a design perspective, end-use becomes a source of innovation. The intentions of technology designers and developers are thus proposals for use, but never the only way. Modern design approaches aim to integrate technology development and end-use activities in frameworks [45], iterative cycles [46] and feedback loops [47]. From the perspective of this stream of design research, the unintended use of heat pumps is not predominantly a risk to realizing design ambitions. Rather, the activities of end users can be seen as a way of adapting technologies to the end-use situation, and even as a form of collaboration between technology developer and end-users.

A performative understanding, inspired by practice theory [48,49]) takes everyday human activity, organized in practices such as heating homes, bathing, cooking, and doing laundry, as the basic unit of analysis. People *perform* these practices in the messy and unpredictable settings of everyday life. The concept of co-performance builds on practice theory [50] and argues that (next to people) technologies, such as heat pumps, are also capable of performing everyday practices; they should be considered as *co-performers*. Bringing this together, our perspective highlights the activities of residents and technologies and how they interact (’their performances’). Our performative understanding also draws on the concept of *scripts*. Scripts, in science and technology studies, are the blueprints for how humans and technologies interact [51,52]. Using this concept of scripts and looking at resident interactions with heat pumps, unintended use becomes a deviation from the blueprint for use, in other words *an improvisation on the script*.

We can further expand this framework, and propose that what happens in households (what residents and technologies do in daily life) are the constituent part of something bigger. Such a view reflects the commitment that in some respects, societal transitions are the sum aggregate of many individual changing lifestyles and daily practices [53]. In performative terms than, what happens in households (interactions between residents and heat pumps) are *scenes* in the *theater play* of the energy transition. (As such this work aligns with recent developments in energy research and transition studies drawing on dramaturgical and performative approaches [54]. The supply side of heat pumps has an orchestrating and responding role towards the scenes. Professional actors in this supply side aim to *direct* the scenes in a way that contributes to the theater play of the energy transition.

To synthesize our brief introduction, from the performative design research perspective we adopt in this study, performances of residents and technologies in each household, together form a scene in the theater play of the energy transition. The word *improvisation* comes to refer to the unintended, unexpected interactions of residents with heat pumps, and other parts of an energy efficient house (e.g., the opening of windows in warm weather). We understand the activities of professionals in the supply side of heat pumps as *responses* to this improvisation. A response is something that professionals do that engages somehow with this improvisation. Responses can be something structural, built in existing workflows (e.g., a service complaint protocol), it can be a one-

time intervention when improvisation is noticed (e.g., an information campaign), or it can be a change in professional practices or standards in response to improvisation (e.g., a new implementation of a service protocol).

In line with our design research attitude, some general principles can already be proposed for what might be effective responses to improvisation. First and foremost, unintended or unexpected use is not necessarily a problem, or something to be prevented. Instead, it is a form of improvisation, which might be directed, orchestrated, or regulated. To cater to this improvisation, we can propose that technologies such as heat pumps are assigned a flexible role in everyday life of residents. Such a flexible role aligns more with improvisational practices, instead of scripted use. Such technologies should be adaptable to diverse use situations ('different scenes') as no end-user situation is the same. On a higher level, we can propose that system designers and other professionals do not just carry out a project and 'leave the scene' but are involved beyond delivery, both by learning how decisions have worked out (a feedback loop) and by proposing and spreading ideas of 'good improvisations'. This involvement then requires connections to the end users by supply-side actors in the heat pump value network.

4. Approach and methodology

Our overall approach relies on interviews for collecting data. The research methodology in this study also incorporates a design element. The video resulting from this design, functions as a stimulus in research. It serves to evoke a reaction from research participants that pertains to their real-life situation and that is relevant to the research problem being investigated. As mentioned, the goal of these interviews is to understand how participants respond to improvisation. The interview had two parts. The first part focused on participants present understanding and recollection of their practices. The second part introduced a sensitizing video as a stimulus and focused on participants responses to this video.

4.1. Design of the sensitizing video

As we have argued above, currently, there are few established connections between supply side and end use in the heat pump value network. We have also argued that the absence of these connections stems from particular understanding of use, which lacks a conception of improvisation, and describes deviations from intentions as mis-use. This aligns with our own observations from earlier conversations with professional practitioners in the field. We have noticed that such unintended use often goes unobserved, and that there is unclarity as to how this unintended use might relate to professional practices. From earlier research, we had also learned that imagining alternative or additional professional practices responding to improvisation was difficult for these professionals.

We therefore decided to prepare and include a sensitizing video in the latter half of the interviews. The purpose of this video has a function similar to a stimulus in experimental research. It is not a suggestion for future practices, but a provocation that serves to evoke a reaction from research participants that pertains to their real-life situation and that is relevant to the research problem being investigated. As such, our approach makes use of speculative design, a method common in design research, where the idea is to introduce design concepts that spark conversation and provoke debate [55–57]. Speculative design is increasingly used as a research method as it can sensitize research subjects in relation to research questions [56,58].

This video served the purpose of creating a baseline understanding of unintended use by the participants, to introduce them to the framing of unintended use as improvisation, and to make them aware of how their practices relate to this improvisation and how they could potentially respond to it. It does so through an explanation and illustration of the perspective introduced above. Concretely, the use context is presented as an improvisation scene. Identifying it as a scene proposes a shift from the technology as the main point of attention, towards an opening idea that there are a variety of actors in the use context who dynamically interact with each other. The existence of a variety of actors, in turn, raises the question of their relationships and what emerges as they interact. Zooming out, participants viewing the video (professionals in the heat pump value chain) are positioned as directors of the improvisation scenes. Identifying them as a director proposes a shift from preventing unintended use, towards an opening idea that the director has choices on what to aim for in the interaction between the scene actors (users and technologies).

The content of the video draws from earlier ethnographic work that we did [5,59] and makes use of the framework as described above (section 3). Earlier ideas and drafts present in the video were presented in workshops with external experts. Based on feedback from this workshop and other stakeholders, these ideas were synthesized in a storyboard and a script for a voice-over (in Dutch) by the first author. Storyboard and script were, through several iterations, developed by an external video maker into an animated video.

The video has a duration of exactly six minutes. It consists of four parts: 1.) an introduction of the energy transition, the role of heat pumps, and the phenomenon of unintended use. 2.) an explanation of how these elements (transitions, technology and unintended use) can be understood from a performative perspective. 3.) three ethnographic vignettes from our previous research [5,59] and three proposed interventions that respond to the described situation in the vignettes, 4.) a list of four principles (following from our perspective presented in section 3) which are used to come up with these responses. The video ends with a provoking question that starts the second part of the interview. Table 1 presents the full voice-over in translation, and several stills from the video.

4.2. Interviews

The interviews were conducted in April 2024. We used purposive sampling, targeting professionals who could provide a good overview of the process. We therefore looked for larger players in the heat pump market in the Netherlands, and spoke to people in managerial, executive or representative positions. The participants were recruited through professional and research networks and trade fair contacts. Many of the participants had decades of experience in the sector and had worked in many positions, including in laborer positions like installer. We also targeted other organizations involved in this sector, that contribute to innovations in the field. These included technical project leaders on heat pump projects for social housing organizations and providers of energy management systems that specifically involve heat pumps (Table 2).

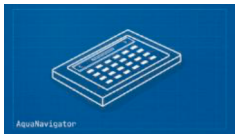
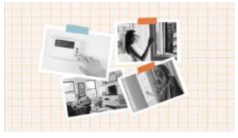
We were specifically interested in heat pumps, but many of these manufacturers and wholesalers are involved with other installations (such as ventilation or PVT-panels) as well. All the participants were male (reflecting the state of the industry).

Semi-structured interviews are a widely used qualitative method in energy-related research [60]. This approach allows for flexibility in exploring participants' experiences and attitudes while maintaining a consistent framework across interviews.

The interviews were conducted in Dutch and followed a structured guidebook to ensure consistency in the questions asked. However, the interviewer maintained flexibility, allowing for a natural flow of conversation and enabling participants to reflect on their own experiences. The primary focus was on capturing participants' attitudes and personal accounts related to the research topics.

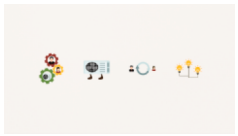
The duration of the interviews varied between 45 and 90 min. While certain essential topics were consistently addressed, the interviewers loosely adhered to the guidebook for other questions. This approach ensured that the interviews remained conversational and reflective. To facilitate this, interviewers occasionally provided examples from previous ethnographic research to prompt discussion and elicit insights into participants' attitudes and practices.

Table 1
Voiceover and stills from the video.

We want to get rid of fossil fuels. That is why many Dutch homes need to be renovated by insulating them and removing them from gas, for example with a heat pump. Great achievements can be made by renovating several houses at the same time and installing a heat pump. For example, in neighborhoods with social housing. The goal is for residents to live in a well-insulated house, where it is warm and which suits their daily needs.	
Once the renovation is completed, the installation does its work. A heat pump heats the house and the hot tap water without natural gas. But while the installation does its work, we expect residents to do something too. But they sometimes do different things than expected and intended. We see that many residents open their windows, while they are intended to be kept closed when it is colder outside. We see that residents use more hot water than estimated. Other residents temporarily turn off the ventilation system, even though they have been told to keep it on.	
Why do residents do different things than we expect of them? And how can we respond to that? To answer that question, it makes sense to view the household as a performance of a play. The play is the energy transition. This play consists of many scenes. Every household in the energy transition plays a scene. The scene has multiple characters. Residents and installations both have roles. The heat pump heats, but it only gets warm inside if the resident keeps the windows closed. The resident can enjoy fresh air, but only if the ventilation system plays its role and supplies fresh air.	
We can partly direct this scene. We can direct the role of residents by, for example, giving them a manual. And we can shape the role of installations by setting and programming them. But, people and technologies play their roles in different ways. A thermostat measures temperature, while a resident physically feels local comfort (and can therefore grab a blanket). A ventilation system works predictably based on measured values, while a resident can plan ahead based on the agenda. In short, people (can) improvise, while installations must be predictable and cannot deviate from their script. We can respond to this. We can encourage, support or give direction to residents' improvisations by giving the right instructions from the director. Let's look at some improvisations and how an intervention that supports that improvisation can contribute to a better scene and ultimately a better play.	
Marijn and Joost live with a family of six in an energy-neutral house. Their domestic hot water system only makes hot water once a day, and that is not enough. Their youngest son therefore sometimes has a cold shower. To avoid the cold shower, the family improvises an overview for the use of hot water every week. This allows them to determine who can shower on what day and when the dishes should be done.	
We introduce the hot water planner. This device makes it easier for residents to plan their hot water use. They can indicate when they expect to need hot water. When the hot water is running low, the device changes color to warn them. The landlord distributes this device to larger families.	
Dave turned the attic into an office. However, the ventilation system is also located in the attic and makes quite a bit of noise; too much for his concentrated work. By searching online forums for the installation guide, Dave found a way to access hidden settings that allow him to disable the system for a period of time.	
We introduce the zero energy doctor. This is a volunteer energy coach. This person knows the details of installations and gathers new insights by talking to residents and monitoring online forums. This person will then explain these insights and apply them to residents in the neighborhood to help make their energy-neutral home work for them.	
Rob and Sacha did some experimenting to get the desired internal temperature. They have discovered that it is much faster and more convenient to regulate the temperature by opening and closing the windows than with the thermostat. Now they keep the thermostat at 22 degrees and open a window if it gets too hot.	
We introduce the experimenting thermostat. This thermostat is available on request for the interested resident. It does not stay at the temperature set by the end users, but experiments with them. For example, the self-learning algorithms will lower the temperature when energy consumption is high, to encourage residents to close the windows. It tries to minimize the number of times users have to intervene while reducing energy consumption.	

(*continued on next page*)

Table 1 (*continued*)

We want to get rid of fossil fuels. That is why many Dutch homes need to be renovated by insulating them and removing them from gas, for example with a heat pump. Great achievements can be made by renovating several houses at the same time and installing a heat pump. For example, in neighborhoods with social housing. The goal is for residents to live in a well-insulated house, where it is warm and which suits their daily needs.	
So, how do these stage directions support the improvisation? We used these principles: Creating a dynamic division of roles between residents and installations such as heat pumps. Set up installations so that they are flexible and correctable, and thus adaptable to the situation. Creating a feedback loop from use to system designer and back. Pick up, monitor and distribute good improvisation ideas.	
How can you give stage directions for improvisation? And how does that contribute to the energy transition?	

In one instance, two participants from the same organization were interviewed together (both of their statements are denoted by P4). Another interview was conducted in two parts, with the participant watching a video outside of the interview sessions. These adaptations were made to accommodate the participants' schedules.

The data generated from these interviews consisted of transcripts. These transcripts were produced using a combination of automatic transcription tools within MS Teams and on-device transcription using AI models, specifically MacWhisper.

4.3. Data analysis

We used reflexive thematic analysis because it is a highly flexible method that readily adapts to different questions and sample sizes [61,62]. The principal researcher took the lead in the analysis process, with the other authors contributing by reviewing the coding results. Initial findings were recorded in a new document to ensure transparency and traceability.

Our analysis was conducted with a critical orientation, meaning that we approached the data with an awareness of the broader social and contextual factors influencing the participants' responses. The analysis was predominantly deductive and theory-driven [61], focusing on specific responses that aligned with our research questions and theoretical framework.

The stages of our reflexive thematic analysis were as follows. 1.) Data familiarization and generating initial codes, while correcting transcriptions for accuracy. 2.) Searching and reviewing potential themes. This initial round, based on a representative selection of the data, was reviewed collaboratively with the other authors to ensure the robustness of the identified themes. 3.) Defining and naming themes, ensuring they were distinct and accurately represented the data. The collaborative review process and critical orientation ensured that our analysis was both rigorous and reflective of the complexity of the data.

Table 2
Participants.

	Organization	Position, current and previous
P1	Heat pump manufacturer	Project coordinator, installer
P2	Social housing organization	Head of innovation
P3	Heat pump manufacturer	Strategic advisor, director
P4 (two participants in one interview)	Heat pump (installation) wholesaler	Product owner and head of R&D
P5	Provider of monitoring and home energy management systems	Director, (co–) owner
P6	Heat pump manufacturer	Director, (co–) owner
P7	Heat pump manufacturer	Head of product management
P8	Heat pump manufacturer	COO, innovations manager

5. Results

5.1. Introduction: responses to unintended use proposed in the sensitizing video

In this results section, we describe how professional practices of heat pump development and implementation as part of the energy transition in the Netherlands, respond to unintended use of heat pumps, or improvisation. Earlier (section 3), we have defined responses as *professional practices that somehow deal with unintended use, or changes to these practices when unintended use is encountered*. We have also, in the sensitizing video, proposed three responses to unintended use. Following our analysis as presented in this results section, these responses can be retrospectively classified as: 'supporting improvisation' (intervention 1), 'spreading insights (intervention 2)' and 'automated regulation' (intervention 3).

In this results section we first describe the (change to) practices brought up by professionals, clustered in seven responses (5.2.). In this section 5.2 we exclusively report on responses indicated by participants before being shown the sensitizing video, or without reference to the video. After that, we report on the factors that, for our participants, inform which response would be chosen (5.3), including the responses shown in the sensitizing video.

5.2. Responses to resident improvisation reported by participants

From our interviews we could distill seven themes that represent participating professionals' responses to improvisation. As will become clear, these responses do not exclude one another and several themes (partially) overlap.

5.2.1. Response 1: Investigation of anomalies

The first type of response to improvisation is to regard them as anomalies. Many of our participants mentioned that they learn about unintended use or improvisation from either energy monitoring setups (as many modern heat pumps are sold with 4G connected monitoring), or from complaints when resident heating or cooling strategies did not achieve their goals. Automated signaling often happens based on threshold levels for energy consumption or for runtime hours of heat pumps. Sometimes this is complemented with additional information from monitoring to determine if residents are home, for example. This

monitoring and signaling of anomalies typically involves multiple actors. Monitoring companies (of which one participated in our interviews) or heat pump manufacturers inform building owners or managers (such as those at social housing organizations) who will then further investigate. Alternatively, residents themselves signal anomalies by filing complaints to their social housing landlords.

When no complaints are made, and no excessive heat pump figures are observed, unintended or unexpected use will likely not be noticed by our participants. Examples of such unobserved instances include ventilation practices, such as opening bathroom windows rather than ventilating with mechanical ventilation systems [P2]. Participants indicated that they were somewhat aware of such situations but also indicated that they felt insufficiently informed about unintended use.

The first thing many of our participants do when they notice deviations from expected performance (through monitoring or complaints), is investigate whether there is a technical fault. Often, in recently finished renovation projects there might be a misconnected pipe or an unopened valve. In some cases, when the issue is still not clarified, investigation continues with further diagnosis and reporting [P1] and a closer look into the performance of other households within the project [P8]. Heat pump resellers and manufacturers see this as a form of aftersales [P6].

Only when the installation not seems to perform as expected, participants will investigate further, and discover that anomalies might originate in what residents do. Throughout this chain of signaling, unintended or unexpected use, will remain in the realm of anomalies to be solved (like technical faults) and tried to be solved case by case. However, participants also noted how the accumulation of such cases leads to learning, which we report in the next subsection. *"When the projected energy savings were not reached, it became clear that the user component has a large influence"* [P7].

5.2.2. Response 2: Learning and transferring learnings

All of our participants (in strategic roles, and as innovation leaders, e.g.,) see many individual renovation and heat pump implementation projects, and thereby have somewhat of an overview perspective. From this perspective, they saw patterns emerging within these projects, and were able to find similarities in multiple cases, related to unintended use. One of our participants, for example, mentioned observing that instructions in booklets about underfloor heating were not picked up by residents in a project. He then included this aspect actively in information events [P2]. Similarly, another participant had assembled learnings across projects in a video that responds to frequently asked questions at resident-oriented events, including those about simultaneous cooling and heating with heat pumps [P1]. Similar learnings also changed technical decisions about heat pump implementation. One of our participants mentioned for example how earlier assumptions about the frequency of taking a shower were wrong, and therefore adjusted the size of the domestic hot water storage in later projects [P1].

However, participants also indicated their struggles to consolidate these learning points along the whole value chain of heat pump implementation. This results in part from the distance between use and supply-side actors. Another reason is that many actors (including installers, but also renovation divisions in social housing organizations) work exclusively in projects and not in development, resulting in a lack of feedback from the use phase, resulting in unchecked assumptions [P5]. During the interviews, some ideas emerged to consolidate learning (especially beyond projects) by doing yearly evaluations together with residents [P2].

5.2.3. Response 3: Anticipating in technology design

All participants emphasized that what residents do is relevant, both to the sustainable performance of the complete renovation, and to the satisfaction of end users who may not (any longer) be able to, for example, obtain 24 degrees indoor temperatures in winter. *"We know that a high thermostat setting leads to trouble"* [P5]. Many participants [P4, P5, P7] indicate that they primarily deal with such unintended use through anticipation in the design and implementation of heat pumps. One of the reasons they anticipate unintended use is that, because compared to gas based boiler systems, heat pumps are 'not as forgiving' [P7]. They describe this as the'boundaries of technical capabilities'. *"In case of all-electric heat pumps, what residents do is very relevant, because they run into the boundaries of technical capabilities more often [compared to conventional gas boiler systems]"* [P4].

However, participants also indicated that these technical capabilities are to a certain extent within their influence and that these 'boundaries' could be expanded to allow for some level of unintended use [P6]. For example, they indicate that if the power of the heat pump or the levels of building insulation are chosen somewhat higher than strictly necessary according to energy performance calculations and/or building regulations, this will make sure that residents do not run into issues even when they do not act as instructed or intended.

Participants expressed different positions towards such 'oversizing' of heat pumps. Some noted that unintended use is to be expected and what they considered normal, an insight they had gained from their experiences in selling and implementing heat pumps. In their view the building regulations account only for a perfect or average use situation, whereas reality shows that each situation deviates from the average (*"there are no 1,4 person households"* [P5]). As such, there should always be some space created for behaviors that were not accounted for in the building regulations or in calculated energy use. *"If installers choose to do the minimum that is going to cause problems"* [P4]. These participants therefore encourage installers (in training) to choose a heat pump with higher power than strictly required and thereby leave some room for unexpected and unintended resident activities.

On the other hand, other participants expressed the view that calculated energy consumption in principle should be achieved. From an energy performance perspective, heat pumps can heat every room in the house to, what is established in building regulations, a comfortable temperature. Oversizing the heat pumps is then considered a risk to the achieved efficiency, and residents should accept lower maximum room temperatures. In this view, it is thus not just the installations that should change in response to unintended use, but residents should change their expectations and behaviors.

5.2.4. Response 4: Preparing mindsets

Another response to improvisation which was mentioned by all participants was attempts to prepare the mindset and expectations of residents. In this regard, all participants, including those with technical backgrounds and orientations, had realized that renovations are not simply matters of technology rollout. Participants highlight that the transition is not just about energy, but also about knowledge [P1].

The participants were largely aware of the limitations and difficulties in preparing or changing the mindset of residents. They are aware that unintended use will happen anyway. *"We know what will happen, especially when it is existing build houses"* [P5]. All participants had realized that a straightforward instruction of use (e.g., to not touch certain buttons [P1]) is not sufficient and does not work to avoid unintended use. Many participants also indicated that explaining the technical functioning of the heat pump is unfeasible in most cases. Aspects like weather dependency and room compensation are difficult to get across [P1].

Instead, participants used a variety of tactics to varying degrees of success. The first tactic is still a form of direct advice to residents but targets one-time changes that will have a longer lasting effect. Participants for example advised residents to not put couches in front of radiators [P6], or to throw out their pajamas because these would not be necessary anymore in a house with more stable temperature levels [P2]. Participants had found that advising such one-time changes was more effective than attempting to change recurrent routines, as these one time changes did not need to be remembered by residents. A second tactic aims to inform residents of the consequences of their use patterns.

Participants tried to communicate to residents that changing heat pump settings could increase the amount of hot water available each day, but also increases energy consumption, and that long showers might lead to cold tap water at the end of the day. A third tactic targeting mindsets relies on the use of metaphors recognizable to residents, or other indirect explanations. One participant, for example, explained how older buildings can be seen as dressed in 'thin clothes' with a 'large furnace' whereas a zero-energy house should be seen as a building with a 'very thick jacket', but with a very 'small furnace' inside [P2]. Participants did also mention that with such use of indirect, non-technical explanations, there is always a risk of misunderstanding or taking the metaphor too far.

The means with which participants were familiar to carry out these mindset preparation tactics include information sheets or booklets that are delivered at installation time, events like resident information evenings or demonstration homes, and the instruction of other actors in the value chain like installers or maintenance parties to achieve a consistent communication strategy. Generally, such mindset preparation happens exclusively before, or at the moment of, delivery. The social housing organization, however, also made use of a six week 'moving in' period after which another event was organized during which further instructions could be communicated.

5.2.5. Response 5: Encouraging and amplifying

Several participants [P2, P3 and P6] reported being aware of, and encouraging a certain level of improvisation. They considered this necessary for residents to gain the required insight into the functioning of their home with new installations. Participants noted that such improvisation and experimentation often only happened for a short period of time. For example, even though changing thermostat settings is generally discouraged, one of our participants thought that some variation in the initial phase could be beneficial. He stated that he thought that residents might change the thermostat up and down for a little bit, and then leave it at some point [P3]. Other participants also indicated that they were not particularly concerned about unintended use. They felt that a subset of residents is always inclined to experiment *"That remains, some people like hacking systems"* [P6].

Another participant indicated that they expected improvisation to happen within a specific time period, which aligned with the information events organized when residents move in. *"We want them to play around with it for about 6 weeks in the beginning, because it gives residents insight"* [P2]. Alternatively, a full year of living with a heat pump would enable residents to experiment and experience effects throughout all seasons [P6].

This encouragement of 'unintended use' indicates a positive and accepting view towards improvisation and potential benefits. As part of this, participants also understood that making use of these benefits and amplifying them works better when residents have a certain openness to change of practices, for example when residents move houses. When residents have recently moved in, they experiment and are able to adopt new use patterns, some of which are useful or necessary for adopting heat pumps *"You throw away the old, and you're open to new rules"* [P2]. This was contrasted with renovation projects where residents stay in the home during the renovation, which they found much less likely to lead to change of use patterns. In these cases, residents continue to perform 'old practices' aligned with gas-based boiler systems, and participants found that their encouraging responses had little effect.

5.2.6. Response 6: Safeguarding

As there was a general awareness among interview participants that a certain improvisation would benefit the residents' learning or was going to happen anyway, participants also sought ways to make this happen in a safe way. They mentioned, for example, that they design heat pump systems in such a way that important or dangerous settings cannot be changed. Certain buttons and valves are put away in a box, intended only for maintenance professionals or installers [P4]. Next to safety, participants mention ensuring energy performance as a reason for putting in some guard rails. Participants mentioned that they *"want to exclude resident behavior"* [P4], as they consider certain behaviors too detrimental to the energy performance of the heat pump. Part of this safeguarding strategy is the limiting of energy consumption. Participants reported that they limited the total flow of hot water out of the domestic hot water storage. This prevents excessive hot water use from extreme use cases. [P8]. On the other hand, participants also used building automation to make sure that even when unintended use happens, resident health will be protected. *"You'll be fine if you [the system] just ventilate based on CO2 levels"* [P4].

5.2.7. Response 7: Directing, accommodating and incorporating

Some participants had developed experience in being responsive to improvisation in a more integrative and accommodating way. These participants do not just safeguard, but also provide subtle cues and guidance to residents that would shape how they interact with heat pumps. One participant [P2] explained how a particular household had felt cold in certain places in the living room. Even though the general advice would have been to move the couch to a different place, in this case, the involved technician simply slightly changed the direction of outlet vents from the ventilation system. Similarly, installers and heat pump manufacturers will often remotely change a setting to accommodate and optimize for a particular use case (e.g., turning off an eco-setting which makes the heat pump produce more domestic hot water for households with higher consumption [P8]). The position of the social housing organization allows for even closer involvement. One of the participants [P2] recalled how a resident had to use the bathroom repeatedly at night due to an illness and was annoyed by the noise. Such frequent use of the bathroom was unpredicted and could be considered unintended use. However, our interview participant decided to temporarily turn off the ventilation in the bathroom, just to provide some more comfort.

In another case, a participant mentioned how residents played around with and changed the settings (the heating curve) of their heat pump. This was reported on an online forum. The heat pump manufacturer noticed this and responded positively. This participant then also went to this residents' home and tested out which settings worked best in that specific case [P8]. In a more extreme example, this heat pump manufacturer incorporated a resident's technical skills in living with their systems within the manufacturers organization. When a resident complained about heat pump interfaces, the heat pump manufacturer offered this person a job, which he took [P8].

These deeply involved, directing and accommodating responses to improvisation tend to be small scale, local and labor intensive at present. Yet the examples show that they brought important benefits for residents: wellbeing, comfort, ownership over and insight into energy use. They also brought important benefits to participating professionals: insight for system optimization and communication with residents, and in an extreme case, acquiring a skill set for their organization.

These directing and accommodating responses also redefine the notion of unintended use, and appreciate it as a form of improvisation. As professional practitioners become more closely involved with improvisation by residents, they work together and propose experiments and different use patterns. Such experiments can also be part of the diagnosis of unexpected issues. Professional practitioners can suggest to try something and see if it works [P8]. This can ultimately lead to optimization or potential redesign of the technology itself.

5.3. Factors for evaluating proposed and new responses

In this section we identify the factors that, according to our participants, shaped which response to improvisation they would choose. This approach will enable us to identify effective best practices (from the listed responses) and investigate what enables or hinders the integration of these responses into professional routines. Determining these factors

also is a starting point for understanding which of these barriers can be taken away. In addition to the responses brought up by participants themselves, identified in seven clusters in section 5.2., participants also benefitted from having watched the video. In the video, as described earlier, participants were sensitized to a particular framing of unintended use, and were introduced to three particular responses (supporting improvisation, spreading insights, and automated regulation).

5.3.1. Observability

While monitoring setups and resident complaints enable professional actors to observe some aspects (e.g., out of the ordinary energy consumption), many aspects of use remain hidden. *"We know about thermostat settings, but not about door openings"* [P2]. Participants highlighted that, even though they found unintended use very relevant, they were limited in the extent to which they could observe it and thereby respond to it. Use related factors often come to the foreground only during investigations or further reports in case of some incident (c. f. 5.2.1.). Observability is thus a factor that hinders choosing more extensive responses.

5.3.2. Positions and responsibility in value chain and network

The value chain of heat pumps has many actors with different responsibilities. As such, manufacturers have previously directed some responsibility to other actors (most notably to installers and maintenance parties) in responding to improvisation [P4]. Meanwhile, they also recognize that installers are seldomly involved beyond the delivery of a project, unless there is a major problem.

Installation wholesalers, from their position in the value network, regard themselves as responsible for delivering installations and their technical performance [P6]. These parties see themselves as limited in further engagement beyond the installations themselves, and do not primarily interact with residents.

On a smaller scale, social housing organizations have some internal distance between those making technical choices and those responsible for end-user. Upon delivery of a project, the responsibility for the buildings in operation transfers from a department responsible for renovations, to a regular 'customer care' department. The responsibility of the former is concerned with energy consumption and household behaviors but only in planning and prediction, while the latter primarily responds to complaints [P2] and is thus more closely involved in the use phase.

Meanwhile, as shown above, these positions in the value chain are changing, enabled by connectivity (4G monitoring) and further spurred on by financial structures such as 'performance guarantees' where building owners are sold heat rather than an installation [P6]. These innovations enable (and require) for new actors to be involved beyond delivery and into the use phase.

5.3.3. Legislation and contracts

Participants reported that legislation and legal frameworks, such as GDPR, restricted them from responding to improvisation. For example, the monitoring company, while able to observe collected data and draw conclusions about unintended use, is, as an external party, not allowed to respond or further investigate [P5]. Although social housing organizations have more possibilities in this respect, they as well are bound by regulations and contracts to not intervene in residents' households. For illustration, they can not directly correct residents when they observe that windows are opened [P2].

Participants also reported that emerging legislation in the Netherlands might require installers to guarantee the performance of heat pumps and resulting energy savings. Although there is currently unclarity about the development of these regulations, participants reported that such regulations could potentially require installation parties to become more pro-active in the use phase in order to guarantee energy savings even when residents do not use heat pumps as intended [P7].

5.3.4. Perceived capabilities of residents

While interventions such as additional advice or household facing monitoring apps are seen to potentially contribute to directing improvisation and use patterns, it is also important that residents understand the information presented to them, and have the capabilities to interpret them [P1, P8, and 5]). Participants noted that they actively struggled with this understandability as heat pumps, and low temperature heating, are new and complicated to communicate to some residents [P7]. The perceived capabilities of residents are thus a factor that determines the responses by professional practitioners in the supply chain.

5.3.5. Technical possibilities

Participants expressed an interest in further home automation, monitoring and automated signaling of deviations to residents. Such a smart system would provide guidance and solve complicated situations in the most optimal way for the residents. *"Ideally, we would have some sort of digital butler"* [P5]. However, participants also felt restricted by technological possibilities. They mentioned that often an ideal response would be an on demand or ad hoc replacement of the installation in case of a change of situation. For example, a larger family moving in needs a larger hot water storage, but a quick replacement is costly and technically difficult. Technical possibilities thus also determine the choice of response.

5.3.6. Perceived norms

Participants expressed that there are written and unwritten norms regarding what is considered 'normal' and strange use. Buildings (and building regulations) are designed for averages. One participant for example mentioned: *"the system is designed for, what is it, 1,4 people? I have never seen a 0,4 person"* [P5]. In some logic, any deviation from these norms can thereby be considered unintended use, but participants highlighted that they used a situated and nuanced norm, for example for the size of households. They would only respond to excessive deviations from this norm, and be less interventionist when they observe more moderate anomalies.

Such a norm was also more implicitly present in the limitation of domestic hot water flow described above (4.2.6). The participant mentioned that such a limitation would not be an issue for most showerheads, while some 'tropical rain shower heads' would not receive enough water. These kinds of showerheads were thereby considered out of the norm [P8].

5.3.7. Organizational capacity

Participants mentioned that they had only limited time and resources available to respond to unintended use. Some mentioned they don't have the capacity to monitor everything [P8] while others reported being too busy to respond and had to *'just wait till it breaks'* [P5]. This pressure is further exacerbated by staff shortage in the installation sector and the current pressure for a fast energy transition [P7].

In a similar vein, participants highlighted that the capacity for innovation and learning beyond single projects is difficult in the complete value chain, as many installers are small and do not have the extra time available. However, currently, the Dutch installation sector is undergoing a consolidation, where larger firms incorporate smaller ones. This consolidation creates the organizational capacity for innovation and new responses [P7].

5.3.8. Resident autonomy and responsibilities

Participants found it important to respect resident autonomy when it comes to energy use, and thereby refrained from responding too early. *"We're not here to force a low energy bill"* [P5]. Multiple participants expressed a negative view towards what they considered 'patronizing' responses [P1, P2]. Social housing organizations were also aware that too much intervention 'behind the front door' can cause internal household conflicts, in which they did not want to meddle [P2]. Instead, many emphasized the need for voluntary participation by residents in

initiatives that guided their use patterns.

Similarly, some participants expressed that they regarded it as their responsibility to advise residents on choosing the right heat pump that would "make them happy" [P4], while how they operate it, is ultimately the residents' responsibility.

5.3.9. *Household diversity and scalability*

Participants emphasized that they aim to tailor their responses, when possible, to specific households. There is a general awareness that residents are diverse, and thereby benefit from different responses. In eco-neighborhoods, for example, there is a high interest to experiment not only with technology, but also with use patterns [P8] (i.e. to improvise), something that participants did not expect from other neighborhoods. Responses that are appropriate to these more experimental settings might not be scalable. In this regard, participants also accept that a certain level of *"hacking is always going to happen"* [P6], but would intervene if this happened on a larger scale.

The education of installers is seen as a way of scaling and repeating the impact of responses. While heat pump wholesalers find it difficult to respond to resident diversity and individual use patterns because of the large numbers of heat pumps they sell, their educational programs can encourage installers to customize their responses [P1 and P7].

6. Discussion

This research highlights the crucial and overlooked role of improvisation in resident practices and the responses of professional actors on the supply side of heat pumps. We have argued that the field has largely been unable to address improvisation because it has lacked a perspective through which to study it. This research has introduced such a perspective and then showed how using it reveals existing responses as well as the potential for the development of new practices. This study is, to the extent of our knowledge, the first to study in depth the responses of professional actors in the heat pump value network to improvisation in households. Compared with earlier work on the relevance of the use phase to the supply side, our results describe in more detail the practices and actions by which heat pump manufacturers, resellers and other relevant actors engage with unintended use. Our results have confirmed that household improvisations we found, turned out to be of critical influence on the goals of the supply side (sustaining business models, accomplishing predicted energy savings locally, and realizing the energy transition at large). These responses emerge from dominant perspectives on value chain configurations, in which end-users and heat pump manufacturers are separated by a chain of resellers and installers.

6.1. *Reflection on the results*

This research showed that when interviewed from a perspective that foregrounds improvisation, professionals in their practice respond in a variety of ways to improvisation (unintended use of heat pumps). The seven responses discussed in the result section expand on our original three responses presented in the video (supporting improvisation, spreading insights, and automated regulation). This brings the total number of responses identified in this study to ten. This research has also identified which factors are relevant to the participating professionals in evaluating and deciding which response to choose. We have identified nine factors. Together, these are shown in Fig. 3. In the text below, the responses are indicated with R1-R10, and the factors with F1-F9.

The seven responses that emerge from the interviews are (although not described in these terms) also present in existing literature to various degrees. The investigation of anomalies (R1), reviewing first the technical performance, followed up by analysis of what users do, is a well-known emerging approach, but until now mostly applied to public buildings and not to homes [63]. Although learning between different

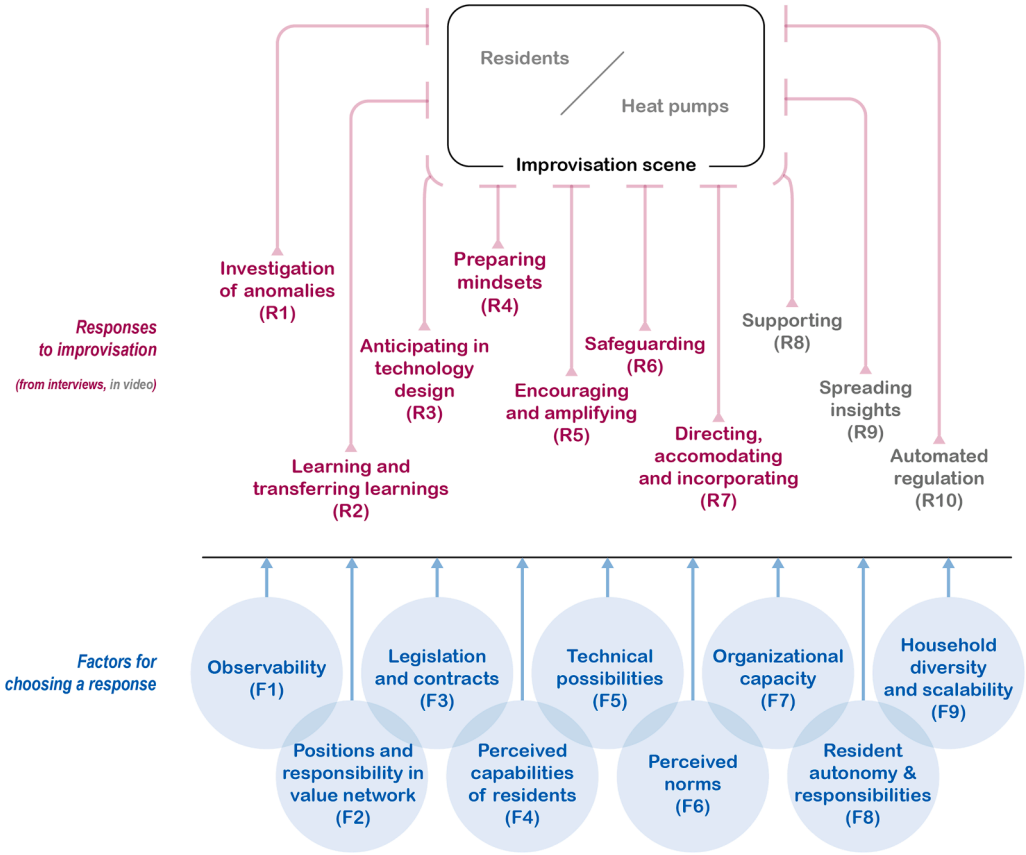


Fig. 3. Results of our study: responses to improvisation (numbered R1 to R10) and factors for determining a response (F1 to F9).

actors in the supply chain is seen as an urgent topic for contributing to energy transitions (e.g., [64]), learning from end-users (R2) is currently rarely discussed in literature. Instead, the focus in the use phase is almost exclusively on technical energy performance. There are however some energy related studies that assign the user a clear role in identifying and solving technical problems [65]. Weigert's study aligns with response R2, but also incorporates elements of R7, as, in his proposal, heat pump users receive simple instructions and guidance for solving technical issues in an experimental way.

Meanwhile, literature in energy performance research increasingly suggest approaches for connecting heat pump supply-side actors and users that integrate some of the responses also mentioned by our interviews. Wade and Visscher [28], for example, mention service related pricing (heat-as-a-service) and performance guarantees as ways in which occupants become engaged in the supply chain. Such new (financial) structures where a single organization oversees the entire retrofitting project, require at least some of the responses to improvisation (e.g., R4: anticipation of improvisation and R6: safeguarding). Similarly, de Wilde and Spaargaren's [33] proposal to consider not only the renovation process, but also the use phase as a complete 'customer journey' suggest a closer connection between supply chain and use. However, this study is not very explicit on what these connections could look like beyond written public customer reviews of supply-side actors. The role of the supply chain interacting with users post-installation is also confirmed by Owen and Mitchell [30]. They highlight that these interactions (primarily in the form of instructions) should respond to users interests and have the potential of guiding energy use. This closely aligns with a directing response to improvisation (R7).

However, the literature details very little of what these new relations between user and supply chain could mean for improvisation or unintended use. This was confirmed by our participants who uncovered the tensions and opportunities that emerge from these business models 'on the go'.

However, there is existing literature on this. Moore et al. [34] mapped different service touch points in the user centered design approach of renovations. This study, firstly, emphasizes the necessity for understanding the system in use. It highlights contact points such as home visits and telephone lines to the landlord or contractors are ways in which the expectations of users can be managed (R4). This study again highlights the importance of connecting to users 'post-installation'. Importantly, this study also finds an significant role for neighbors in influencing heat pump use. This aligns closely with our own proposed response of spreading insights (R9). Moore et al. also discuss the adjustment of settings in collaboration with and according to the preferences of residents. This aligns with the regulation (R10) and accommodation (R7) discussed in our study. The authors [34] also mention that this is an area that requires significant research as it will be difficult to ensure adjusted settings are energy efficient. These factors were also discussed by our participants (F5 and F9).

Another high-level approach that includes several of the collected responses, is proposed in literature on the role of households in transitions. Here, the emphasis is on everyday life as a source of expertise, and of user innovations [26] [5]. This work also confirms the role of online forums as a way of collecting and spreading insights (R7 and R9). While this work on transitions primarily targets governments, the approach could be integrated with supply-side activity as suggested in our study, in particular responses that create a direct and more immediate feedback relationship between use and development (R5, R7, and R9).

The ten responses do not exclude one another, and in an important sense also rely on each other (e.g., one has to notice an anomaly first, before it can be further directed). The different responses require different capacities and labor from actors in the supply chain. For example, while an investigation of anomalies (R1) is (initially) relatively straightforward, the 'preparation of mindsets' (R4) requires a lot more effort. It also requires roles and expertise that heat pump manufacturers, as companies with a primarily technical expertise are less familiar with. The various responses require time and effort from actors in different stages of the process. Anticipation (R3) and preparation (R4) happen primarily in the earlier stages of a renovation project. Meanwhile, it should be emphasized that, according to our participants, these responses are also part of a feedback loop, and inform further actions in the same and other projects.

The interviewees displayed a strong interest in the role of the user side. However, they also showed some hesitance towards intervening too strongly. This might be in part a consequence of their historically distant position in the supply chain from end-users (F2). But they also frequently mentioned the autonomy of residents (F8). This factor was specifically mentioned in relation to responses that more noticeably intervene what residents do (R7, R10). Interviewees expressed that they did not want to be too directive, or too interventionist, but rather stayed in the background with responses that are less identifiable as their actions.

A final observation is that participants were reluctant to discuss societal norms (F6) as relevant in informing their responses. Words like 'normal' were often used in reference to energy use, thermostat set temperatures or shower durations, but without a clear reference for what informs these norms, and how they (could) change.

6.2. *A new perspective for the supply side of heat pumps*

One of the objectives of this research was to investigate how a new perspective that connects the heat pump supply side to use patterns in households highlights areas for new relations between them. Our study opened a perspective towards closer relationships between end users and the heat pump supply chain. From our performative perspective informed by design research, unintended use is not a set of failures that are to be eliminated but a set of positive approaches that can be integrated and built upon and that potentially adds value to the value chain. This perspective gives more texture to what Killip et al. [35] describe as the potential for a 'value-driven commitment to reducing building environmental impacts' shared between the heat pump supply side and end-users. Realizing this potential requires closer relationships involving communication, education and feedback loops with the 'quality of friendship' [35] and a large role for various forms of trust

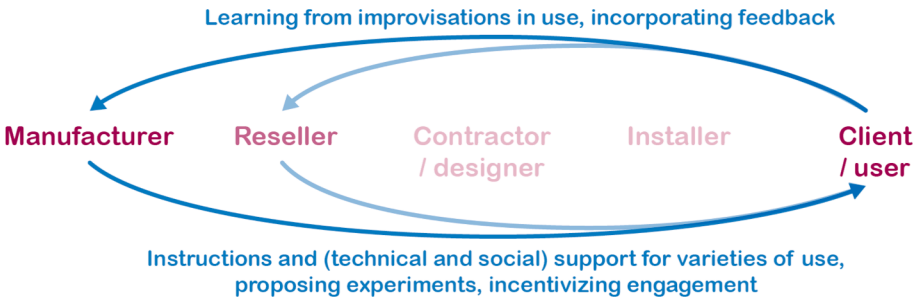


Fig. 4. New relationships in the heat pump value network.

Table 3
Summary of our discussion: Responses from different perspective, and potential for amplifying these responses through socio-technical innovations.

Response of supply chain actors	How the responses relate to current perspectives on the value network	How the responses could relate to a proposed new perspective of relationship building in value networks	Implications: Socio-technical innovations with potential for amplification of new relationships
Investigation of anomalies	Aimed at optimizing performance and preventing or repairing technology or user faults.	An integrated part of a feedback loop, where anomalies form part of a learning cycle that is of interest to technology development	Monitoring setups and feedback mechanisms (similar to complaint lines) that can observe relevant aspects of use (and not just faults).
Learning and transferring learnings	Learning within projects, where lessons remain tied to specific use cases.	Learning over the course of different projects, where lessons are integrated into technology development and future project structures.	New organizational structures (e.g., innovation divisions) and setting up closer connections between different actors in the supply chain. Making time for innovation and improvements over the long term.
Anticipating in technology design	Avoiding 'problems' for residents.	Deliberate anticipation of, and a flexibility for buildings to be adapted to diverse use patterns.	Developing heat pump and installation designs that are flexible to diverse situations (by e.g., being modular).
Preparing mindsets	Preventing misuse and setting correct expectations for end-users.	Preparing end-users for continued learning.	Providing learning materials on the use of heat pumps, which are dynamically updated based on resident feedback.
Encouraging and amplifying	Allow some improvisation, as it cannot be prevented entirely.	Encouragement of improvisation as a driver of learning for both end-users and supply chain actors.	Creating platforms for sharing user experiences and innovative uses, incentivizing user (and community) engagement.
Safeguarding	Prevent residents from acting in ways that might harm energy performance.	An integrated approach which allows for diverse use patterns without compromising safety or energy performance.	Developing guidelines and smart systems that can automatically adjust settings to maintain closer to optimal performance and safety.
Directing, accommodating and incorporating	Removing (potential) causes of discomfort for residents.	Building long-term relationships between residents and the supply chain.	Paying close attention to existing places of resident feedback (e.g., online forums) and establishing new channels for continuous communication and feedback, incorporating resident suggestions into ongoing product and service improvement. Proposing experiments to end-users.
Supporting improvisation	[n/a]	Support for improvisation by end-users as technology developers can learn from this.	Creating adaptive interfaces, automations (e.g., smart thermostats) and household tools that can accommodate and potentially encourage resident improvisations.
Spreading insights	[n/a]	Discovering and finding where improvisation resulted in valuable insights for improving energy performance, and spreading these insights among other households.	Developing platforms and networks for knowledge sharing, possibly facilitated by digital tools and social media.
Automated regulation	[n/a]	Enabling both foreground and background roles for heat pumps which facilitates many different use patterns, rather than just the intended use.	Implementing systems that, automatically and/or with intervention from supply-side actors (e.g., remote change of settings) can adapt to user behavior and environmental conditions.

between all actors [66]. This potential is enabled by innovations such as performance monitoring, post-occupancy evaluation informing design decisions, renovation as a product [67] and experimental approaches to energy transitions such as living labs. This new perspective is aimed at integration, feedback loops and with an appreciation of households as actors and co-innovators in energy transitions (Fig. 4). Such a view recognizes that in the current context, no longer is the design process something that happens before production; rather, we see an inter-twining of development and deployment. In this sense, design becomes more about the dynamics of relations between end-users, technologies and actors in the supply chain ('co-performance'), instead of designing precisely the intended use of a technology [68].

Both of these perspectives (the dominant view linked to current configurations where unintended use is seen as risk (3.1.), and the emerging view towards new network relationships where unintended use is seen as improvisation (3.2.)) are present in our results. In the table (Table 3) we further distinguish them. As the three responses we propose in the video were specifically informed by the new perspective, and not by the current value chain configuration, the second column is empty in these three rows.

The emerging perspective towards new relationship was (at least in part) suggested by the video we used as a (provocative) stimulus to generate knowledge. This video was developed as part of this study. It was based on a much longer engagement with the field, and developed in a design cycle that included reflection on earlier ideas with potential participants in a workshop. While it was successful in eliciting responses in the interview that incorporated this perspective, the video itself was also a prototype tested for its functionality in reframing unintended use from an old to a new perspective in this particular audience. Upon watching the video, many of our participants commented on how it closely connected to our earlier discussions about their activities and views on unintended use, which we had discussed in the first part of the interview. Participants were also successfully able to distinguish the presented perspective as notably different from the dominant view in the field. Several participants were able to quickly point to or come up with innovations or structures that align with the newly introduced perspective (column 3 and 4 in Table 3). They were also quick to identify where concrete proposals, such as the interventions presented in the video, were not the most feasible or desirable responses and challenged by many existing structures in the field (such as legal frameworks and other factors F1-F9). Some, but not all, participants quickly adopted the vocabulary presented in the video (referring, e.g., to residents as actors in a scene). However, the question remains if the (temporary) change of perspective adopted when watching the video had any lasting effect in the future professional activity of interview participants. Participants need to get used to new ideas and perspective and paradigm changes. Realizing this change in practices requires a much deeper and longer embedding of these thinking probes (or stimulus) in organizations and practices [69].

6.3. *Towards socio-technical innovations*

In general, one of the objectives of this research was to establish a perspective that connects the heat pump supply side to the diverse, unintended, dynamic, and potentially innovative, use patterns in households. Based on the evaluations of the different responses (section 5.3), we also propose ways in which the forming of these new relationships can be amplified through socio-technical innovations. These can be found in the last column of Table 3. They are not all entirely novel. However, their contribution lies in their alignment with a

proposed perspective of openness to improvisation. With this perspective, we offer a way for value network actors to move beyond an underdetermined 'normal' response and instead embrace a path towards an exploration of use. Potentially many more could be identified.

How do these socio-technical innovations produce effects in line with the new perspective? These proposals are socio-technical innovations, innovations that integrate social and technical perspectives and interact with both social and technical phenomena [8]. This means that they go beyond a narrow focus on technical improvements, but they also go beyond a narrow focus on social improvements. Socio-technical innovations do not (directly) address technological optimization of heat pumps, but do integrate technologies when they benefit the goal of these innovations: to form new relationships between heat pump use and supply side. What these proposals have in common is an acceptance that improvisation with heat pumps will happen, while also recognizing that this improvisation can be guided, directed, and even incorporated in the heat pump supply-side activities. These proposed innovations also propose an explicit space and time for improvisation. It might, e.g., be most beneficial to encourage improvisation when residents have newly moved in. Similarly, it might not be necessary (or feasible) to involve all end-users of heat pumps in a feedback loop. Instead, more attention can be paid to willing, enthusiastic or influential residents in specific neighborhoods or other environments (such as online forums). Ultimately, these socio-technical innovations should benefit both heat pump design choices, and their performance (in terms of efficiency and delivery of comfort), but this research has highlighted that the journey towards these optimizations requires improvisation and response.

Another key aspect to highlight about these proposed innovations is that they rely on feedback loops. These feedback loops are both short (e.g., changing certain aspects of a heat pump or its programming in a project when it is in use) and long (e.g., learning about end-users from executed projects and incorporating lessons in future projects through e.g., post-occupancy evaluations). The proposed innovations rely on (early) participation of residents. This engagement goes further than passive sharing of information or quantitative monitoring. We acknowledge that this requires time, effort and (interpersonal) work. It is possible that the technical actors on the heat pump supply side have less familiarity and explicit skills in the interpersonal domain. The heat pump value network encompasses various potentially conflicting values among actors, with business models, innovation, and energy performance goals not always aligning seamlessly. Potentially new roles should emerge, or roles should shift to bridge the technical and social domains. While our focus lies on business actors, assigning responsibility to the heat pump supply side for reducing energy consumption in everyday use might also benefit from new policies from governments (subsidies, regulations, etc.) [27].

Our study made use of and proposed a particular perspective, one informed by design research. This perspective has enriched our view of the relationship between the supply side of heat pumps and use. Such a perspective is not the only one, and arguably many different perspectives are necessary for succeeding in increasing the rate, depth and success of heat pump renovations in the energy transition. We hope we have contributed a part in creating room for socio-technical interventions.

Future work should develop the illustrative socio-technical innovations into more concrete and realistic interventions that work in practice. Our research has revealed the factors of importance to value network actors that should be considered in this development. In parallel with such an action-oriented approach (required to increase the rate, depth and success of heat pump renovations), there is also a need to reflect on and further develop our understanding and sensitivity to the role of heat pump end users. Currently, there is a lack of knowledge of situated action in household and the factors that determine and disturb everyday practices (such as the introduction of new technologies). A design research approach is valuable for developing both knowledge and interventions in a continuous and co-creative feedback loop. Given the high level of uncertainty and complexity in this field, initial attempts at socio-technical innovations may not be successful, underscoring the need for experimental approaches and spaces and feedback loops to foster innovation in protected niches.

The qualitative nature of our study presents several limitations. The results are illustrative and insightful but might not be generalizable to the whole heat pump supply network or beyond, due to the limited number of participants. While we aimed to provide an overview of the Dutch heat pump sector, our analysis was based on reported practices (responses) rather than direct observation. Additionally, many practices we encountered were not evaluated in detail and were sometimes mentioned only as ideas or one-time occurrences rather than consistent, structural practices. Consequently, the applicability of these responses remains uncertain, and we did not rank or evaluate them comprehensively. Our study also excluded numerous factors, such as early phases of product development, the moment of installing heat pumps and the construction period.

7. Conclusions

The objective of this research was to innovate in the relationship between sustainable technology suppliers and users, using the example of heat pumps. We have done so by uncovering existing and new connections between the heat pump supply side and the diverse, unintended, dynamic, and potentially innovative, use patterns in households. We have established a design research perspective that appreciates practices of use as improvisation, and the activities of the supply side as responses to this improvisation. Through a video, we have shared this perspective with actors in the heat pump supply side. We have collected their responses to improvisation, both suggested in the video and in their professional experiences. We have proposed ways in which these responses, from our perspective, could be amplified in socio-technical innovations that connect heat pump value chain and improvisation in use. We have argued how such socio-technical innovations are estimated to contribute to energy efficiency and better relationships between households and heat pumps.

CRediT authorship contribution statement

Evert van Beek: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stella Boess:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis. **Alessandro Bozzon:** Writing – review & editing, Supervision, Methodology. **Elisa Giaccardi:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

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

Acknowledgements

This work was supported by the Rijksdienst voor Ondernemende Nederland. This project is implemented with support from the MMIP 3&4 scheme of the Ministry of Economic Affairs & Climate Change and the Ministry of the Interior & Kingdom Relations. The authors would like to thank the participating professionals.

Data availability

Data will be made available on request.

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