Bandwidth heating: Exploring temperature ranges for economical heating

Graduation Report Integrated Product Design, Delft University of Technology

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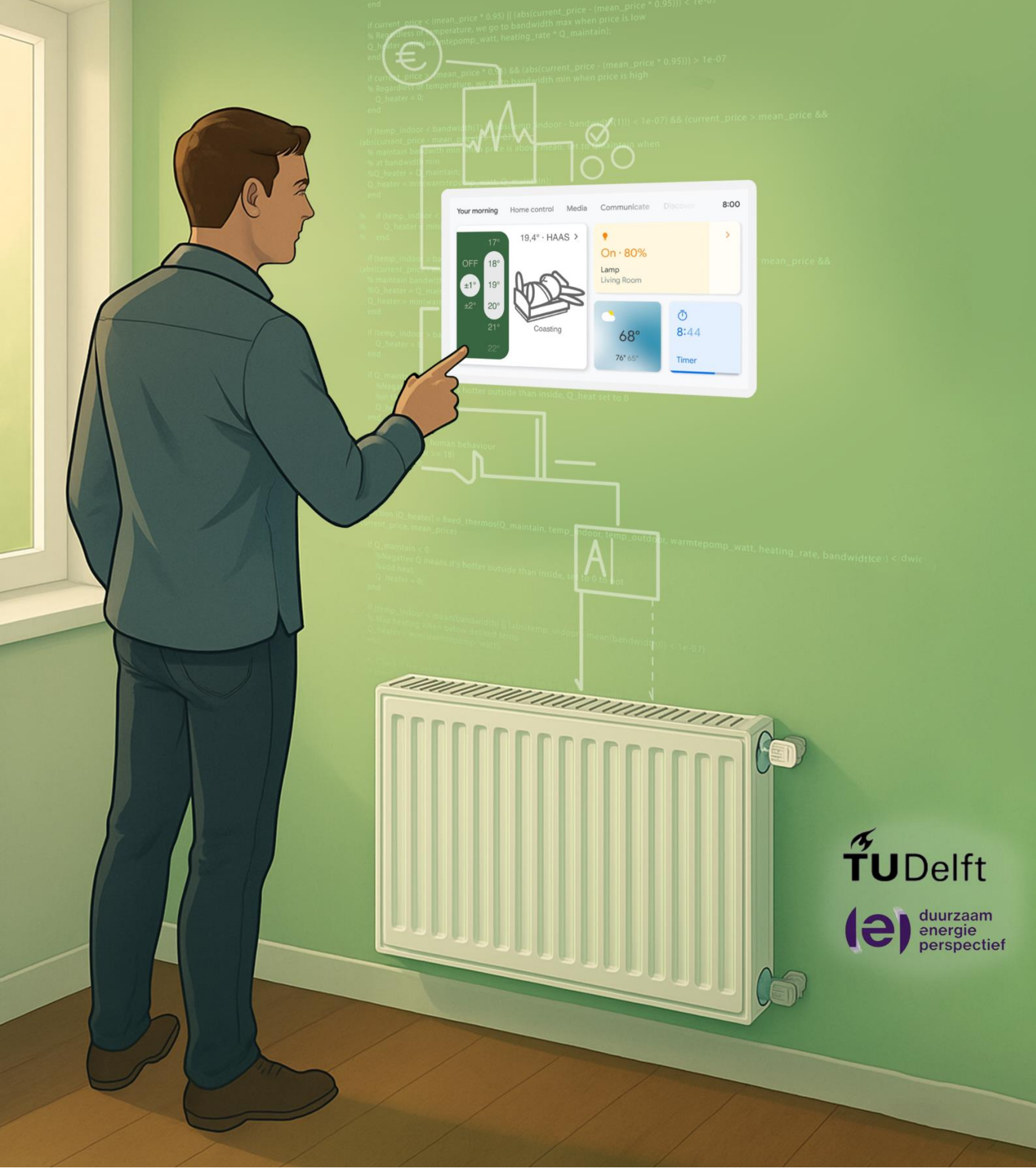

TU Delft

duurzaam energie perspectief

Master Thesis Title

Bandwidth Heating: Opportunities of temperature ranges in economical heating.

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Title page image was partially generated, then manually adjusted to include the correct UI, code and other project specifics to fit to this thesis.

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Summary

This thesis investigates how the performance and appeal of heat-pump-fed district heating (HPDH) systems can be improved, offering a sustainable alternative to traditional gas boilers. HPDH systems are important in the transition to renewable energy sources and becoming a low-carbon society, but adoption faces challenges.

Central to the project is the concept of bandwidth heating, in which users agree to a temperature range rather than a fixed setpoint. Research supports how small temperature ranges are perceived as comfortable, at slow drift rates (rate of temperature change). Due to the slow thermal inertia of heating homes, this comfort applies to this design. This flexibility enables a shift of heating draw toward periods of low hourly energy prices and high renewable availability, providing cost savings and additional environmental benefit. Simulation results demonstrate that bandwidth heating can significantly lower heating costs by up to 15% while increasing the share of consumed renewable energy. This dynamic system maintains user comfort in these small fluctuations of temperature, making them a more competitive heating solution. When hourly prices are high, the system coasts. When prices are low, the system allows heating. As influxes of renewable energy exert downward pressure on the energy price, cheap electricity is greener too.

The project introduces a Heating-as-a-Service (HaaS) model, combining the technical optimization with a user aspect. The HaaS model shifts focus from individual ownership to a subscription-based service, through which bandwidth heating is offered. This distinction carries more agency for the system. This approach enables this cost-effective method and brings opportunities for more innovation within this service.

Users are supplied with a novel HaaS interface, through which they can select their preferences and parameters within which the system may optimize. It is developed and tested with users, revealing that most participants are excited about the cost savings bandwidth heating can offer. The interface features more elements such as savings comparisons, social cues and an introductory tutorial to ensure all users are comfortable and knowledgeable of the system. In testing, users noted how automation is welcome if its benefits are evident, so a comparing graph is made part of the interface where the daily consumption of HaaS is compared to a fictional fixed thermostat consumption under similar conditions.

Built with system development, technical modelling in MATLAB, and interface prototyping, the result is a scalable, user-centric product-service system that supports the transition toward smarter, more sustainable heating by making HPDH a more competitive product.

View the complimentary poster for more elaboration.

Lay Summary

This project explores how to make district heating systems more affordable. These systems use heat pumps instead of gas, which is better for the environment but they're not yet widely adopted.

The idea at the heart of this project is called *bandwidth heating*. Instead of setting one exact temperature, you choose a comfortable range (like between 18°C and 20°C). This flexibility allows the system to heat the home when electricity is cheaper. Tests show this can reduce heating costs by up to 15% and make better use of green energy. To make this system easy to use, an interface was designed that helps people interact with the system. This was tested with users, who responded positively, especially when they saw how it could save them money.

The result is a new kind of heating approach: smart, automatic, and better for the planet without asking users to sacrifice comfort. It helps make sustainable heating an attractive and realistic choice for everyone.

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1. Introduction

1.1 Context and Background

At this moment, space heating is largely carried out through radiators fed from a gas kettle. Powered by fossil fuels, these decentralized heat sources represent a large challenge to overcome when transitioning to more sustainable methods of heating due to its convenient appeal and, up until a few years ago, reasonably predictable costs. The field of space heating has branched out to develop substitute methods, from which the heat pump has surfaced as a promising method. The heat pump draws energy from the power grid, as opposed to fossil sources. It uses this energy to extract heat energy from the air and send to heating systems in homes.

In the development of this system, a laboratory in Duiven can reenact circumstances the heat-pump might encounter to assess its performance (Figure 1). This laboratory is equipped to test possible technical aspects of the system but cannot replicate the unpredictability of human use.

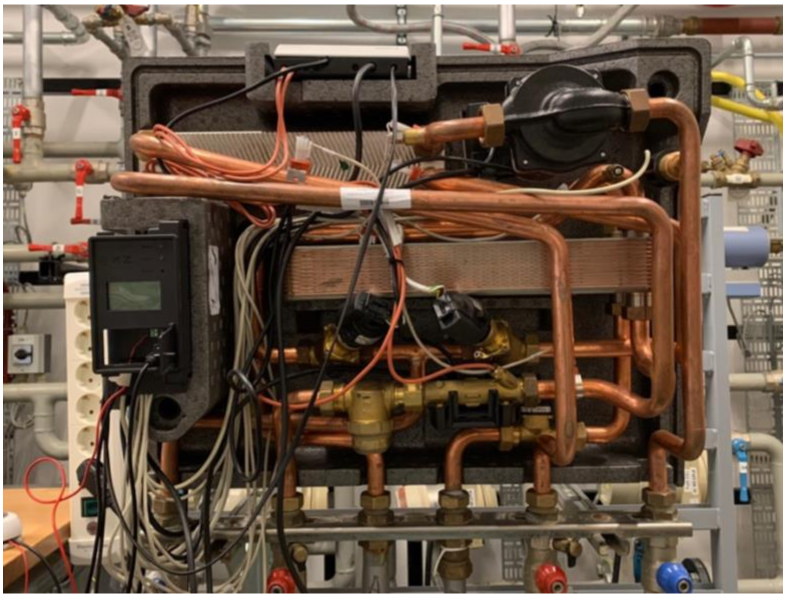


Figure 1: Heat Exchanger in Duiven Laboratory

Alliander is an umbrella corporation for subsidiary companies, under which *Duurzaam Energie Perspectief* (DEP). DEP develops and implements district heating systems powered by a *Modular Energy System* (MES, Figure 2), which houses an array of heat pumps, gas kettles and buffer tanks. A heat pump works by circulating a refrigerant, through expansion valves and compression the refrigerant is processed in such a way that energy transfer is achieved by altering the boiling and condensation point. Its composition is designed for its neighborhood of implementation. This is a high temperature system to allow provision of tap water as well and is hereafter referred to as *heat-pump fed district heating* (HPDH).

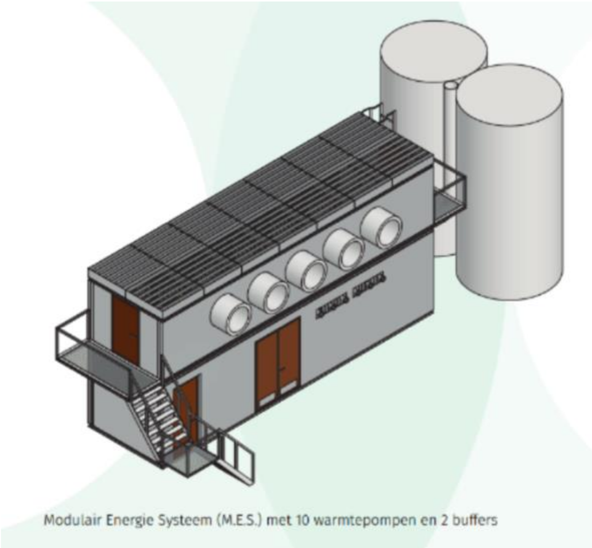


Figure 2. Modular Energy System that feeds HPDH

The MES serves as the heat source in HPDH and can modulate in temperature and flowrate. In homes, heat is extracted from the system through a heat exchanger which in turn provides hot water for the homes: district heating is a closed system and does not directly feed taps in homes. Figure 3 is a simple example of how the pipes address homes in a neighborhood.

Figure 3. HPDH integration into a neighborhood

This report defines bandwidth heating as a promising design for heating systems connected to the electrical grid; these systems are subject to day-ahead energy pricing. By using a small bandwidth over the desired temperature, the homes can be used as a heat battery. The mechanism relies on being able to modulate the temperature, and ride on the heat capacity of the home to bridge moments where energy is more expensive.

1.2 Problem Statement

HPDH systems present a sustainable and decentralized alternative to traditional gas boilers. However, adoption faces a key challenge: existing thermostats are not optimized for HPDH, leading to less competitive heating costs as they fail to take advantage of fluctuating energy prices and their inert thermal inertia.

1.3 Optimization Potential

During the project, bandwidth heating emerges as a potential optimization strategy. This allows users to predefine a desired temperature range rather than a fixed point. This fluctuation allows the system to target the lowest-cost heating periods.

While bandwidth systems hold promise (Chapter 2), its novelty causes a disconnect between users and system, as existing thermostats are not designed to engage with this new approach. Bandwidth heating requires adequate engagement and insight through a novel dedicated interface. This presents an opportunity to rethink how users interact with heating technology.

1.4 Research and Design Objectives

Aligned with the project brief - *Designing for household contribution to efficient utilization of heat-pump fed district heating systems* - the main objective is to develop a functional bandwidth thermostat with interface and prove its viability, desirability and feasibility. The key objectives are:

- Prove the efficacy of bandwidth heating by coding the desired behavior and exposing it to meteorological and energy price datasets to compare it to a traditional thermostat.
- Ensure user accessibility by designing an interface that meshes with technology familiar to consumers and allows for cost transparency and control of the new thermostat.

1.5 Relevance and Contribution

By focusing on both the implementation of bandwidth heating and its feasibility, this thesis contributes to sharpening HPDH to a more promising alternate space heating solution. The research provides evidence for the viability of bandwidth heating, as well as a strategy to reduce costs for end-users and have HPDH become a competitive product. Here, bandwidth heating is the designed mechanism. Additionally, by integrating an interface, the project offers insights into household acceptance of a novel heating system. The findings from this thesis are relevant to district heating development, policymakers, product engineers, users and DEP.

1.6 Research Questions

This thesis seeks to answer the following key questions:

1. What are the key technical features and challenges of HPDH, and how can balanced heating utilization influence efficiency from both the user and provider perspectives? (What is the current state of, and what are trends in district heating systems?)
2. What product-service systems are currently used in similar infrastructures, and how can they be adapted or improved to promote the efficiency and user-friendliness of HPDH? (What do competing thermostat products offer?)
3. How do users experience HPDH, and what factors influence their acceptance, usage patterns and user experience? (What are current user behavior and preferences regarding heating systems?)
4. Which thermostat behavior balances user comfort and cost optimization?
5. Which interface characteristics are desirable for a district heating system?

1.7 Project Scope

This thesis is started with the primary objective to design a method to reduce heating consumption within district heating networks.

Designing for household contribution to efficient utilization of heat-pump fed district heating systems.

This brief initially aimed at decreasing peaks in consumption as to allow for reduction of heat buffers in the system. Early research and stakeholder discussions reveals that consumption is not the primary issue as buffers are cheap and accessible to add to HPDH, but rather the cost-competitiveness of HPDH compared to conventional heating.
The implementation of HPDH faces challenges, as it is not always a cost-competitive alternative to conventional gas boilers (NOS, 2024). This challenge shifted the focus toward economic benefits for users, making the project more attractive and positioning HPDH as a competitive option in the heating market.
The scope does not include system governance structures, regulation on heat provision, customer recruitment or technical component dimensions. Instead, the scope is centered on how the system operates in practice and how user interaction could be designed with an interface to enhance usability and acceptance.

The challenge is to develop an optimized thermostat based on an efficiency metric, to increase the desirability of HPDH systems. To support its adoption and complement the functionality, an interface design accompanies the product as the portal between user and system.

1.8 Stakeholder Mapping

Scoping out the field of involved parties (Figure 4) highlights three key players in HPDH development: DEP, its parent company Alliander, and end-users, emphasizing the importance of aligning the product with their needs. Other stakeholders, such as policymakers, municipalities, and research institutions, hold varying levels of influence and interest but are less directly involved in this concept development and building stage. The design primarily focuses on those actively shaping the system, with broader engagement serving to build support. This report can be used as a targeted effort to convince more distant stakeholder of the importance and desirability of this design.

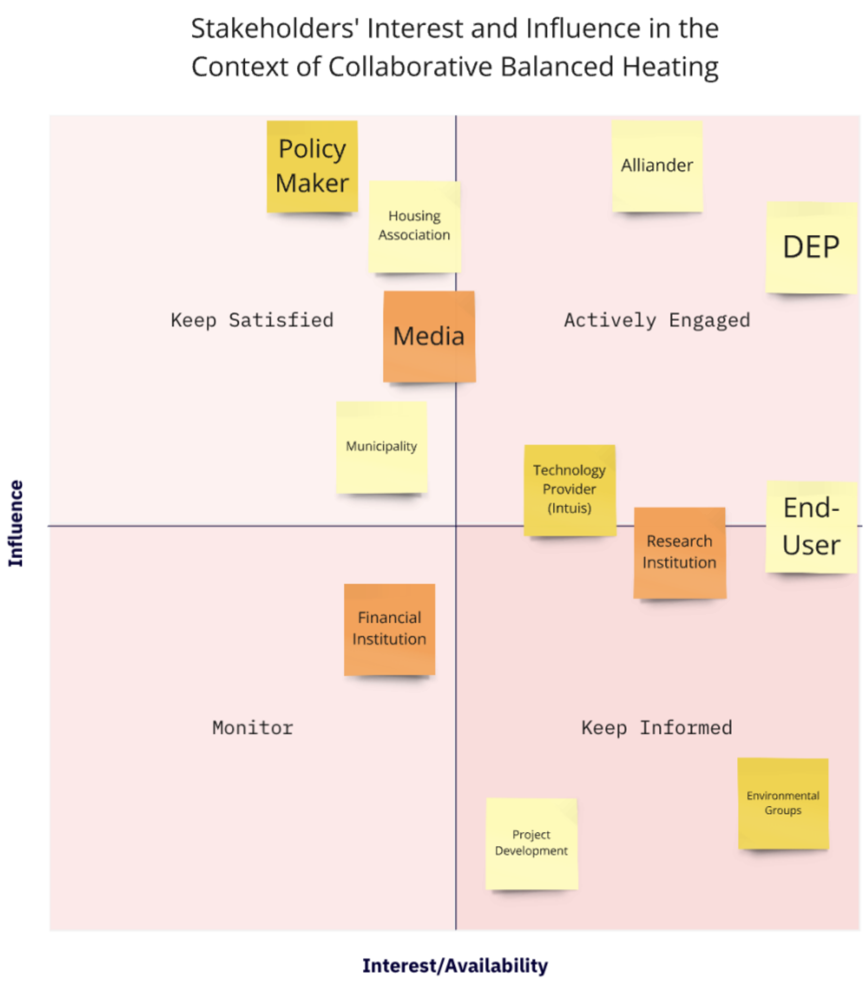


Figure 4: Stakeholder map

2. Contextual Analysis: District Heating Trends and Bandwidth Comfort

PURPOSE

What? – To design an effective solution, it is important to understand the broader district heating landscape, trends and developments within this sector. The role of Alliander in this market and how they are shaping their product aids in tailoring a design. Furthermore, the comfort considerations of temperature ranges in bandwidth heating is researched.

Why? – District heating is undergoing changes due to evolving regulations and technology. The impact of these trends on HPDH influences the design, and understanding it allows to align the design with prognoses. Lastly, in determining the benefits of bandwidth from a cost-perspective, it is important to know whether fluctuations in temperature influence user comfort.

How? – These aspects are explored through internal and literature research, guided by a research question:

- What role does Alliander play in the transition to HPDH, and how does their concept align with industry challenges and opportunities?
- What are the key technological and market trends shaping the future of district heating, and how do they impact feasibility of HPDH?
- To what extent are temperature ranges comfortable?

2.1 Alliander in the Energy Transition

Alliander is an umbrella for many subsidiary companies. Operations cover the industries of providing gas and electrical connections to homes and businesses. This makes them a key player in the Dutch energy transition. Core goals of Alliander include transitioning to a gas-free future and cutting carbon emissions with 49%, from 1990 levels, by 2030 (Alliander, n.d.). Duurzaam Energie Perspectief (DEP), operating under the Alliander umbrella, is developing a district heating system that is fed by heat pumps (HPDH). This aims to transition space heating from gas to electric. The system is decentralized compared to large powerplants but is a much less fragmented option than installing one heat pump per home.

After the Didam concept, the next implementation is taking shape in Loppersum. This will differ technically and in governance. Alliander may act as the commercial supplier of heat in this install, granting more control over costs for consumers. Project managers account for a connection density of 50. Different to Didam, homes that will take part are freestanding.

FINDINGS

Result: Alliander positions HPDH as a scalable solution for the energy transition.
Insight: Direct involvement in heat supply allows cost mechanism flexibility.
Opportunity: Aligning the design with cost-optimization mechanisms and projected Didam circumstances enhance credibility.
Requirement: The bandwidth mechanism must account for Didam circumstances (freestanding homes, local weather) in calculating benefits.
The bandwidth mechanism must use cost-optimization mechanisms.

2.2 District Heating: Trends and Developments

Heat Roadmap Europe (HRE) estimates that district heating will make up 50% of the European heating market before 2050 (David et al., 2017). Up to 30% of district heating will be powered by large-scale electric heat pumps. David et al (2017) emphasize the importance of retrofitting existing buildings to incorporate HPDH, and with the overcoming of the challenges it is concluded that HPDH as a technology is mature enough to be pursued.

In recent years, articles have started including 5th generation district heating and cooling to the development of district heating systems (Lund et al., 2021). This is not, as the name suggests, a logical succession to the 4th generation systems that Alliander is developing. The 5th generation entails more fragmented heat pump placements within buildings where heat exchange is facilitated by a grid. The 5th generation pushes towards individual heat as opposed to the 4th generation's focus on efficiency. The 5th generation district heating is defined by its ability to transfer heat within the system from home to home. This could be beneficial in district heating that tailors to homes of differing size, sun exposure and heat demand or heat production entities such as factories being included in the grid. This is less relevant in smaller grids. Due to similar weather conditions and homes, this transfer of heat is unlikely in Loppersum. The repetition of building size and shape between homes makes it so that their heat requirement under their shared local climate is expected to be near-equal, so that exchange of heat will not occur. Lund, et. Al. (2014) urges the necessity for further development of 4th generation district heating for smart thermal grids; "*an energy system in which smart electricity, thermal and gas grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system*". One way of combining and supporting grids is using the MES as a power-sink for periods of excessive renewable energy generation. It is acknowledged that 4th generation must be further developed to meet the expectations in the future, mostly related to low-temperature grids.

In Europe, a study investigating the implementation of technologies to facilitate fluctuating renewable energy sources in the Danish energy system concludes that large-scale heat pumps are the most fuel-efficient and cost-effective method to circumvent excess electricity production (The Institution of Engineering and Technology, n.d.).

Denmark is a leader in district heating research and implementation. One way they support grids is using heat pumps to sink excess renewable energy into. The concept of MES is relevant in this context, with a similar role. This is further emphasized by a study by Mathiesen et al. (2011), concluding that large-scale heat pumps are paramount for integrating wind energy into the energy system and environmental benefits are parallel to financial benefits. Averfalk et al. (2017) also conclude that HPDH is a promising stabilization of variable power supply as seen from renewable sources. Benefits of implementation pertain to both consumer and operator of HPDH with noise pollution and energy storage as main points of improvement (Mazhar et al., 2018).

Total greenhouse gas emissions in the EU are steadily decreasing. Eurostat reports a 31% decrease since 1990 (eurostat, 2019). Those working in heating are bestowed with the task to contribute to the goal of cutting emissions, this could be a role for HPDH.

Experts identify difficulties in technical maturity and development, the above literature indicates a promising and essential role for HPDH in a renewable energy system of the future. Tereschenko & Nord (2018) strengthen this in researching future trends of district heating and conclude district heating has potential for achieving a low-carbon society.

FINDINGS

Result: HPDH is a viable and desirable technology for future energy systems, a method to integrate fluctuating renewable streams into the grid but its implementation depends on costs.
Insight: Low-temperature grids and integration with energy networks present key opportunities in the district heating market.
Opportunity: A mechanism that leverages flexible heating strategies aligns with identified renewable goals.
Requirement: It must be proven that the designed control mechanism allows to optimize heating based on cost while aiding renewable energy grid-integration.

2.3 Bandwidth Comfort

Bandwidth heating allows for the heating system in a home to fluctuate within a pre-determined temperature range. This is opposed to it attaining a specific set-point, and heating as soon as the measured indoor temperature falls below that threshold. This brings up the question: How do temperature fluctuations impact user comfort?

To answer the question, literature revealed that thermal comfort in humans has shifted paradigms. P. O. Fanger proposed the Predicted Mean Vote (PMV) model in the 1970's where thermal comfort is determined by strict setpoints for mechanically ventilated spaces. Brager and De Dear (1998) introduced their Adaptive Comfort Model (ACM) around the turn of the century, where physiological acclimatization, habituation and behavioral adjustment. This perspective acknowledges that thermal comfort perception goes beyond strict setpoints, and considers the possibility to adapt to a range of temperatures. Luo et al. (2018) conclude that tight requirements are not necessarily linked to thermal comfort and Hensen (1990) concludes that temperature changes of less than 0.5 K/h go unnoticed, and up to 1.5 K/h does not produce evidence of discomfort. Ciuha et al. (2019) found that personal thermal comfort zones vary, where Ivanova et al. (2020) conclude that a gradual temperature drift between 17°C – 25°C is rated equally comfortable to a fixed 21°C space, even listing potential health benefits from temperature fluctuations.

ASHRAE Standard 55 (2017)states a preferable indoor climate in homes to be between 67 and 82 F (19 °C – 27°C). Zhang et al. (2016) conclude that Standard 55 is too strict. Their research delves into thermal comfort during direct load control strategies to alleviate peak demand, where the conclusion is that temperature drifts beyond the Standard 55 determined limits are experienced as thermal comfort. This study tested between 22 and 24 degrees Celsius, with a relative temperature drop from outside temperatures with air-conditioning. It may not be fully representative of effects in cold conditions where heating is applied. Furthermore, it is concluded that *thermal alliesthesia* is beneficial: a temperature drift towards a desired temperature is already comfortable before reaching the desired temperature. Lastly, the speed of temperature drift is linked to perceived comfort. The quicker a temperature change happens, the less comfortable it is perceived.

FINDINGS

Result: Temperature ranges are not inherently linked to discomfort when changes are gradual and temperature does not go beyond personal thermal comfort zones. Literature indicates a temperature moving towards a set point, is rated as comfortable before it reaches that set point.
Insight: The perception of comfort is not strictly tied to a setpoint but influence by rate of change, expectation and context. Slow temperature shifts may enhance comfort, deviations and drifts do not inherently cause discomfort. Users may accept temperature ranges if they can adjust it to their personal thermal comfort zone.
Opportunity: Dynamic bandwidth heating could consider user personalized thermal adaptation; having a user configure their own heating profile may lead to acceptance.
Requirement: Personalized bandwidth settings allow a user to set their desired adaptive comfort profile (temperature threshold, drift rates, eco-modes).
Thermal adaptation relies on expectation, static temperature feedback must be accompanied by temperature inertia expectations, visually support comfort and trust.

2.4 Conclusion on Literature

HPDH is positioned as a viable and scalable heating solution, aligning with district heating trends and the energy transition goals of the key player Alliander. Their pilot project indicates technical feasibility. Their involvement in the second implementation unlocks the opportunity for influence in pricing and steering mechanisms. Literature confirms district heating is key to future energy systems, with particular focus on its capacity to integrate renewable energy sources. Gradual temperature fluctuations do not inherently cause discomfort, this supports the concept of bandwidth heating from a comfort viewpoint.

Design Requirements

Table 1: Generated design requirements from research

#	Requirement	Validation	Development Focus
1	The bandwidth mechanism must account for Didam circumstances (freestanding homes, local weather) in calculating benefits.	Feasibility Viability	Coding: Integration of climate data and house parameters.
2	The bandwidth mechanism must use cost-optimization mechanisms.	Feasibility Viability	Coding: Implement price-steering mechanism.
3	It must be proven that the designed control mechanism allows to optimize heating based on cost while aiding renewable energy grid-integration.	Feasibility Viability	Coding: Both cost performance and green/grey energy consumption plotted to assess.
4	Personalized bandwidth settings allow a user to set their desired adaptive comfort profile (temperature threshold, drift rates, eco-modes).	Desirability Viability	Interface: Implement method to adjust settings to preference.
5	Thermal adaptation relies on expectation, static temperature feedback must be accompanied by temperature inertia expectations, visually support comfort and trust.	Desirability Viability	Interface: Visually include temperature trends / system behavior.

3. Design Landscape: Exploration and User Insights

3.1 Heating Behavior Survey

PURPOSE

What? – To design a system that effectively engages users, understanding their heating behavior, preferences and willingness to change.

Why? – This insight helps determine where opportunities lie in design, and which demands are paramount to success. This shapes the feasibility and desirability of the design and whether participants are willing to engage with heating innovations.

How? – A survey is distributed through QR-codes in shops in Leiden, Nijmegen and Groesbeek, at the faculty of Industrial Design Engineering and through word-of-mouth. Responses are anonymous, with some general demographics collected to assess representation of the larger population. Additionally, 12 participants expressed interest in further collaboration in concept development.

Key Results

The survey results (Appendix A) produced an interesting insight into the available market for HPDH, user behavior and preference. The survey collected 43 responses.

- About 70% of respondents have influence over the decision making of their energy contract. This is either as homeowner or renter. These respondents represent the addressable market for HPDH.
- About 90% of respondents assess their home to be in a decent- to well-insulated state, this makes them serviceable with HPDH due to gradual heating.
- About 65% of respondents are currently serviced with a gas kettle heating system. This shows a large portion of respondents to be subject to gas prices, to which HPDH will be an economical substitute. Furthermore, a gas kettle heating system requires few modifications to be fit for HPDH.
- About 50% of respondents adjust their heating (multiple times) daily. At the other end of the scale, 30% of respondents rarely ever adjust their heating. I conclude half of users value a sense of control over their heating system. This behavior could be driven by desires to be economical or comfortable. 30% of users exhibit desirable behavior for HPDH, though their motives are unclear. It could be their thermostat is programmable already, or their insulation provides enough comfort
- About 40% of respondents declare to be actively looking for ways to reduce their heating consumption. Another 45% says to be open if an accessible solution would be proposed to them. This shows opportunity for HPDH implementation.
- About 30% of respondents note that they either have no control over changing heating systems or no desire, the rest of all respondents say to value a cheaper to operate and more sustainable system as most important pillars.

User control and heating behavior

Result: 50% of users interfere with their heating systems daily
Insight: Users prefer a sense of involvement in their heating, but in HPDH excessive adjustments lead to inefficiency, costs and worse performance.
Opportunity: Incorporating an interface or mechanism that offers a sense of control or insight to substitute direct control, while attaining the goal to prioritize cost effective sustainable heating. This could guide user behavior.
Requirement: The system must be able operate autonomously while providing users with an intuitive sense of control through visual feedback.

Reducing consumption

Result: 85% of users are interested in reducing their heating consumption
Insight: This motivation aligns with the goals of HPDH, which can be emphasized to persuade neighborhoods to adopt HPDH.
Opportunity: This emphasis can be leveraged; any cost savings or sustainability aspects must be highlighted and proven. A feedback mechanism could provide information on savings.
Requirement: The system must actively promote and display cost savings in a transparent way.

Adoption potential

Result: 70% of users have influence on their energy contract. 65% use gas kettles.
Insight: These users are in a position to switch, and their system is easily converted.
Opportunity: A sufficiently attractive outcome of the design process has access to a large addressable market. Designing a user-friendly transition could persuade more users to switch heating systems. This can be strengthened through simple onboarding, clear information and transparent cost structures.
Requirement: The mechanism and interface must be validated for end user desirability through testing.

Collaborative

Result: Users familiar with district heating mention paying for consumptive neighbors.
Insight: This could lead to less motivation to monitor oneself on consumption. District heating is inherently more communal than individual systems.
Opportunity: A way to introduce a type of collaborative nature in HPDH, without it requiring active contribution or significant effort. Some methods to introduce this could be through sustainability scoring, community goals or performance incentives.
Requirement: A non-intrusive method of collaboration finds its way into the final product: either through shared efficiency, adhering to a standard or through another mechanism.

PURPOSE

3.2 Smart Thermostats: Features, Market and Limitations

What? – Modern thermostats enhance user-system integration by providing control and insights into home heating. They build upon traditional thermostats with added functionality beyond temperature adjustments.

Why? – Their popularity is driven by the unique benefits they offer, cost-saving potential, convenience and improved integration. Thermostat potential is significant here, as 60% of warm water usage in district heating systems is used for space heating (Serban & Popescu, 2008).

How? – This space is explored and popular products in this sector are analyzed.

Key products include the Eneco Toon, Google Nest, Tado and Eve offerings (Figure 5, above). Toon offers heating insights, smart home integration and smart scheduling but requires an Eneco subscription and must be professionally installed. Google Nest features learning capabilities and remote heating control but relies on additional products for zoning. Tado and Eve are radiator controllers used for zoning, with Eve being an Apple HomeKit product.

Despite their benefits, these products face notable limitations. Product reviews reveal compatibility issues with the home heating system (gas kettle), especially prevalent with the Google Nest. The Toon is slowly phased out, functionality is declining. Consumption insights are limited to monthly flat bills, and the ‘smart’ functionality relying on geofencing or is limited to a timer. Lastly, all thermostats attain a target setpoint temperature when it comes to heating, flexibility is only offered through ECO-modes or manual intervention.

This analysis of key smart thermostat products reveals features and limitations in the current space heating market, that are used to define requirements in the design process.

FINDINGS

Consumption Insights

Result: Existing thermostats provide limited insight into consumption and costs, limited to flat monthly summaries and not real-time data.
Insight: Users lack immediate feedback on their heating behavior, reducing integration.
Opportunity: Providing feedback mechanisms of system behavior may result in more informed heating decisions and reinforce conscious behavior.
Requirement: The system must provide real-time consumption feedback to enhance user awareness and decision-making.

Automation and Adaptability

Result: Smart thermostats automate heating based on schedules, geofencing or manual input. Dynamic adjustments based on cost or energy availability is currently inexistent.
Insight: Current automation methods either require manual intervention or rely on predefined modes, limiting its adaptability to HPDH-specific challenges.
Opportunity: HPDH-specific automation modes, such as bandwidth heating, are a unique development that may excel in improving HPDH feasibility.
Requirement: The system must display an effective automated cost-optimization strategy that is more economical than a fixed temperature thermostat.

User Control

Result: Thermostats focus on fixed setpoints, providing minimal feedback on system behavior.
Insight: Users may struggle to understand how heating operates in the realm of temperature ranges in bandwidth heating.
Opportunity: An intuitive representation of the bandwidth mechanism, can enhance trust through a less opaque model.
Requirement: The interface must visually communicate selected bandwidth, making selections easily understandable.

3.3 Rapid Prototyping: Identifying Opportunities

PURPOSE

What? – Testing gathered insights, the design process is rapidly explored. This builds on previous research and user feedback.

Why? – By going through the design process in a pragmatic and quick way, key concepts can be validated early, and guiding design requirements can be formulated.

How? – The design in one day method allows focus on rapid prototyping, quick decision-making and iterative testing in a condensed timeframe.

The results from this method are placed in **Appendix B**, as the outcome is not relevant to the greater project. The method did produce insights relevant to the interface development, and important constraints.

The interface for the heating system must balance automation with user engagement. Upholding transparent cost structures aid in developing trust in the system. A key challenge is managing user expectations in unfamiliarity with bandwidth systems. Heating-as-a-Service is a new concept and is subject to the mentioned challenge. Additionally, the interface must remain intuitive while prioritizing key information relevant to the novel heating system.

FINDINGS

Result: The sprint reveals insights and constraints for the project.
Insight: The interface must balance automation with user engagement. Transparent cost structures build user trust in the system. Some influence into heating by the design is required, giving up full control over the heating by the user requires a sensitive approach.
Opportunity: The method identifies an opportunity for Heating-as-a-Service (HaaS), where the service aspect allows some influence into heating characteristics. This aspect is also an opportunity for the interface to adopt HaaS and generate a unique and recognizable interface.
Requirement: The interface must display intuitive visual cues to communicate with users.
User interference allowance should be restricted to temporary adjustments, where the system autonomy remains central.
Costs are transparent, detailed and offer estimated savings.
The benefits of bandwidth heating must be easily understandable.
The structure and conditions of Heating-as-a-Service must be easily understandable.

3.4 Defining Core Functions and System Dependencies

PURPOSE

What? – Exploring the foundational elements shaping the design, the design scope is laid out. The objective is confirming feasibility by defining core operations and technical boundaries.

Why? – By understanding the parameters of the design process, the project focus remains on what is essential as well as foregoing unnecessary complexity.

How? – A functional analysis clarifies these system functions and dependencies.

The first assessment is revisiting how the technical composition of the system and the desired functions are scoped (Figure 5), preventing overcomplication.

The MES is not central to the development of the bandwidth thermostat and interface. Other technical aspects, such as the underground piping of HPDH, software communication protocol and specific component definition fall outside of the scope. In concept-building these are not yet relevant. Any corporate structures behind energy delivery are left out of scope, as this does not contribute or interfere directly when proving the concept of bandwidth heating. Intrinsics of the power grid, including specific load shedding capacities or wholesale (*grootverbruikers*) penalties are out of scope.

In scope is the operation of a bandwidth system and in turn the Heating-as-a-Service model. This is at the core of the design. Aspects such as users, interface development, weather and energy data will aid in developing the design to prove feasibility, viability and desirability.

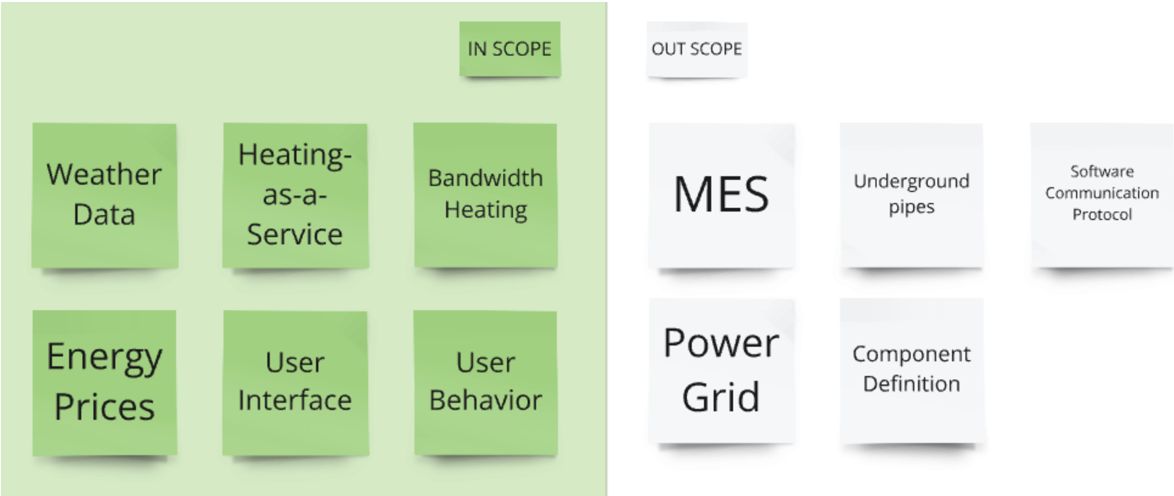


Figure 5: Scope division in design process

The functional analysis defines the core operations of the design and their interdependencies (Figure 6). Each function is assessed based on its inputs, outputs, and intended effects to establish a structured framework for development.

The core functions of the design are **bandwidth heating, pre-heating, collaborative measure, heating-as-a-service, tiered pricing** and **transparency in costs**. These functions are interrelated: **pre-heating** operates within **bandwidth heating**, leveraging lower energy prices to raise temperatures efficiently. **Collaborative measures** encourage shared responsibility and align user behavior with system efficiency. HaaS shifts heating from a direct user-controlled process to a managed service, allowing the HPDH operator to optimize system performance while ensuring user comfort. Cost transparency fosters trust by demonstrating tangible savings, while tiered pricing discourages manual user intervention, reinforcing system stability.

The figure shows how bandwidth heating is a source of dependencies, revealing its importance. The initial broad conceptual framework is processed towards a defined system setting the stage for further design and development.

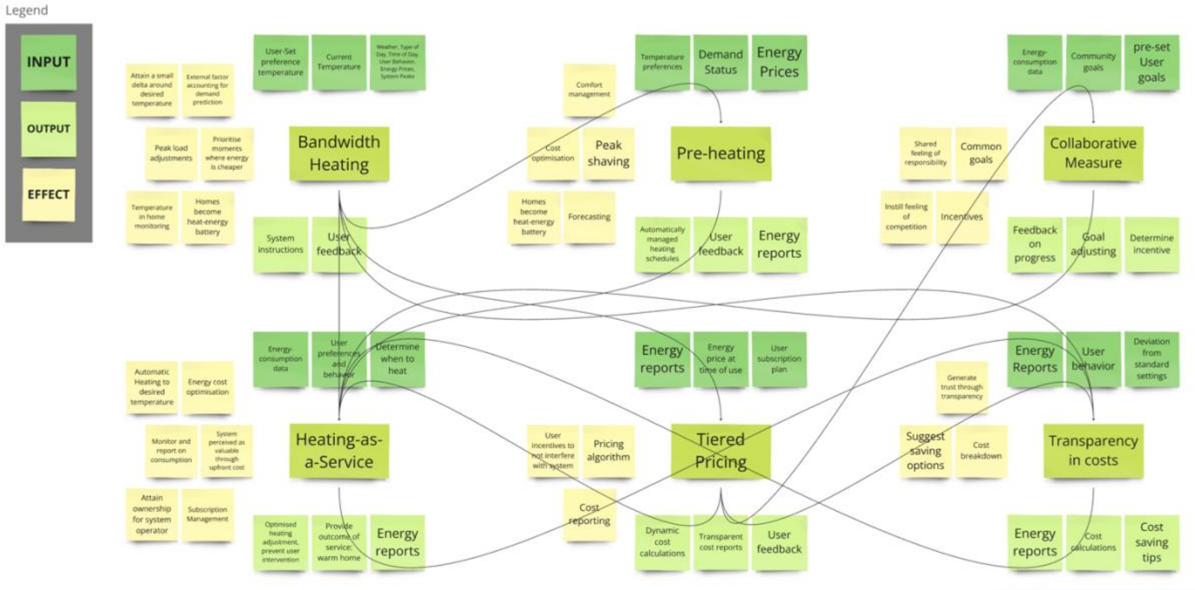


Figure 6: Core functionalities and interdependencies

System architecture

As a final part of the functional analysis, the functions and insights are synthesized into a system architecture map (Figure 7). This diagram illustrates how functions interact and how data flows through the system. This gives insight into how the development of a control algorithm for the bandwidth heating could operate, which inputs it requires and reveal bottlenecks or oversights and can be tested with user scenarios. The bandwidth control algorithm is at the core of this design and its efficacy determines success of the project. Figure 7 is a representation of projected bandwidth behavior, as prices change over the day the system switches between coasting and heating while staying in bandwidth. Closely cooperating with the bandwidth is the interface; the portal of communication between user and system and the determinant factor in desirability of the design.

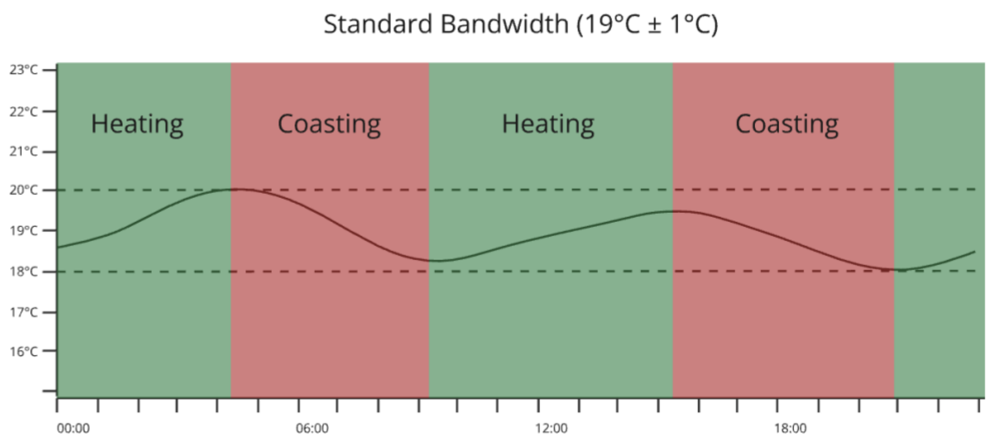


Figure 7: Representation of bandwidth behavior over time

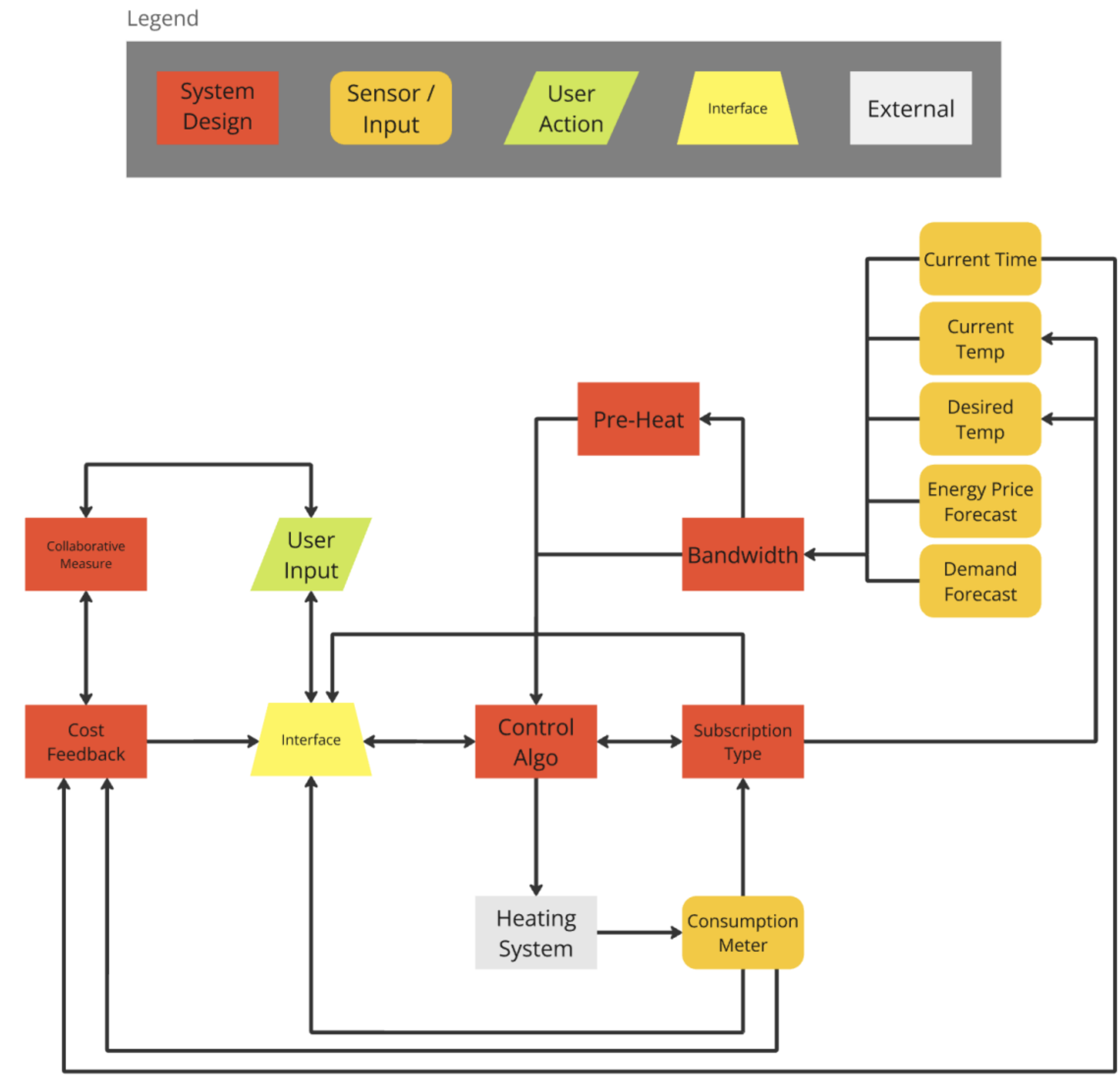


Figure 8: System architecture development map

Walking through user scenarios affirm the interdependencies and logical pathways through the system. Reading from top to bottom (Figure 9), the scenario walks through desired behavior of the system. First reading energy prices, deciding on heating approach, registering consumption and feeding information back to the user. More user scenarios are visible in Appendix C.

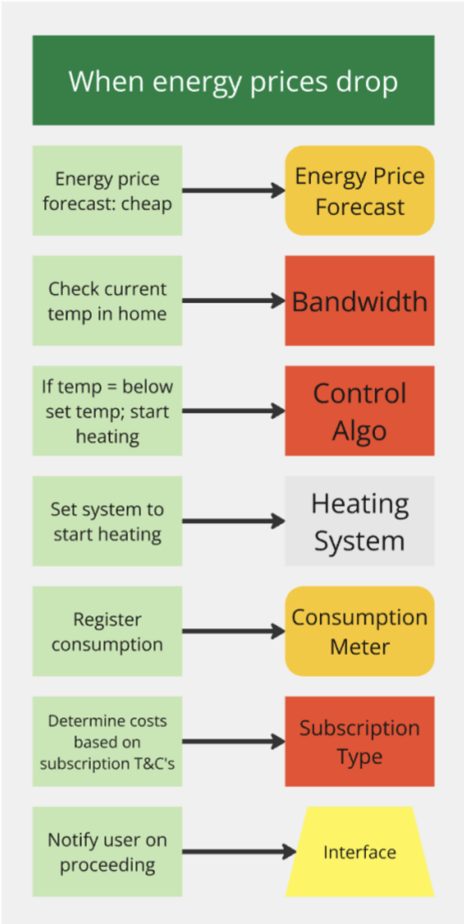


Figure 9: One of several tested user scenarios in system logic

FINDINGS

Result: The system processes real-time energy prices, user interactions and consumption data to determine heating strategy.
Insight: Data-driven decision making is essential for system operations.
Opportunity: Using real-time data allows for automated bandwidth steering based on realistic metrics and provides justified results.
Requirement: The system must support real-time data processing and use it to determine its strategies. These inputs are energy pricing, weather conditions and indoor temperature conditions.

Result: The system operates with many interrelated functions, including bandwidth heating, collaborative measures, Heating-as-a-Service.
Insight: The syncing of functions balance user comfort, bandwidth steering and financial incentives.
Opportunity: An integrated system can optimize energy use while influencing user behavior positively.
Requirement: The system must integrate bandwidth heating, collaborative measures while providing the Heating-as-a-Service model.

3.6 List of Requirements

The research methods generate requirements for the design project. Key user needs and functional insights have emerged. Translating them into requirements assures that development of the design will align with findings. The requirements pertain to different aspects of the system; either coding or interface. These relate to the logical definition of the system and its functionality, and the visual portal between user and system. The concept proposal will be tested against this list of requirements.

Table 2: Generated design requirements from all prior research

#	Requirement	Validation	Development Focus
1	The bandwidth mechanism must account for Didam circumstances (freestanding homes, local weather) in calculating benefits.	Feasibility Viability	Coding: Integration of climate data and house parameters.
2	The bandwidth mechanism must use cost-optimization mechanisms.	Feasibility Viability	Coding: Implement price-steering mechanism.
3	It must be proven that the designed control mechanism allows to optimize heating based on cost while aiding renewable energy grid-integration.	Feasibility Viability	Coding: Both cost performance and green/grey energy consumption plotted to assess.
4	Personalized bandwidth settings allow a user to set their desired adaptive comfort profile (temperature threshold, drift rates, eco-modes).	Desirability Viability	Interface: Implement method to adjust settings to preference.
5	Thermal adaptation relies on expectation, static temperature feedback must be accompanied by temperature inertia expectations, visually support comfort and trust.	Desirability Viability	Interface: Visually include temperature trends / system behavior.
6	The system must operate autonomously while providing users with an intuitive sense of control through visual feedback.	Feasibility, Desirability	Coding: Implement automation logic Interface: Display system status
7	The system must actively promote and display cost savings transparently to build user trust.	Viability, Desirability	Interface: Display consumption/cost metrics
8	The mechanism and interface must be validated for desirability through user testing.	Desirability	Interface: Conduct A/B, iterative user testing to refine

9	A non-intrusive collaboration mechanism must be integrated into the final product, whether through shared efficiency, adherence to a standard, or another approach.	Feasibility, Viability	Interface: Include subtle social nudge
10	The system must provide real-time consumption feedback to enhance user awareness and decision-making.	Feasibility, Viability	Interface: Provide instant feedback on user interference
11	The system must demonstrate an automated cost-optimization strategy that is more economical than a fixed-temperature thermostat.	Feasibility, Viability	Coding: Comparing bandwidth to fixed, economical benefit must be clear
12	The interface must visually communicate the selected bandwidth, ensuring users can understand and adjust settings easily.	Desirability	Interface: Feedback to communicate selected bandwidth through animation or color-coding
13	The interface must include intuitive visual cues to effectively communicate with users.	Desirability	Interface: Use icons, animations and feedback loops
14	User interference should be restricted to temporary adjustments, ensuring the system remains autonomous in managing heating efficiency.	Feasibility, Viability	Coding: Implement optional time-limited manual override system
15	Cost details must be transparent, with a breakdown of expenses and estimated savings displayed clearly.	Viability, Desirability	Interface: Clear understandable cost breakdown and savings
16	The benefits of bandwidth heating must be easily understandable for users.	Desirability	Interface: Provide explaining element
17	The structure and conditions of Heating-as-a-Service must be clearly communicated and easy to understand.	Viability, Desirability	Interface: Introduce tiered plans, comparisons and examples.
18	The system must support real-time data processing using energy pricing, weather conditions, and indoor temperature data to optimize heating strategies.	Feasibility, Viability	Coding: Integrate real data.
19	The system must integrate bandwidth heating and collaborative measures while effectively implementing the Heating-as-a-Service model.	Feasibility, Viability	Interface: Present collaborative benefits and service model effectively.

Chapter 4: Design Roadmap

The vision is to create a seamless and intelligent heating system where **bandwidth heating** is delivered through a **Heating-as-a-Service (HaaS)** model. By shifting control from individual ownership to operator-driven optimization, the system ensures lower costs, better efficiency, and proactive support. Users remain engaged through an intuitive interface that provides **transparency**, guidance, and **collaboration**, working in tandem with a **smart heating algorithm** to maximize comfort and sustainability. Research reveals a clear market gap for a tailored product between user and system.

Synthesizing reveals several key directions of development for this project.

1. **Interface & Functionality** - What does the interface of a bandwidth product look like, and what functionality is desired?
2. **Bandwidth Feasibility** - What is the feasibility of bandwidth heating and how does it operate?
3. **Cost Transparency** - What does cost transparency look like to a user and how is it communicated?
4. **Tiered Pricing & HaaS Structure** - How is tiered pricing, based on deviations from a baseline, structured if offering HaaS?
5. **Collaborative Measures** - What collaborative measures can play into efficient use and how intrusive can this be to users?
6. **User Interventions** - How can user interventions in the heating system be processed or destimulated?
7. **HaaS Onboarding** - What does HaaS onboarding encompass and which information about the system is most critical to share?
8. **Data Privacy & Security** - What data privacy measures does HaaS require and how does this influence collaborative measures?

Bandwidth and interface development paths are prioritized as they are fundamental in proving the concept. Understanding the interface functionality validates its usability and desirability. Proving efficacy of bandwidth heating validates feasibility. These validations are prerequisites in forming the foundation for further development.

Development

The requirements outlined in Chapter 3.6 inform these development paths. Chapter 5 explores bandwidth behavior, testing and code development. Chapter 6 builds on by focusing on the interface, interaction and visual feedback.

Chapter 5: Code Development

PURPOSE

This thesis investigates whether a bandwidth mechanism improves heating efficiency, measured through costs. To test this, a bandwidth mechanism is coded and tested against realistic data to approximate its efficacy. A separate 'fixed' thermostat, adhering exactly to a specific temperature, is modelled as comparison. The development of this code contributes to the overall system as it is at the core of the design and proving it lays the foundation for further development.

The core hypothesis is: "The larger a bandwidth range is, the more economical it will heat, with consumption remaining near-equal.". This is based on a larger bandwidth having more leeway in which it can decide on heating behavior and shift its operation more towards the cheaper hours. A bandwidth averages out towards the center value, the yearly consumption should be similar to a fixed bandwidth.

Additionally, the model produces insights into demand balancing and peak shaving. A secondary hypothesis is: "Collaborative heating can be achieved by staggered heating to induce peak demand shaving.". This aims to research whether shifting heating behaviors through time, peak load on the system can be reduced which in turn can reduce the dimensions or components in the *MES*. This does not aid economical heating, but separately focusses on demand.

5.1 Code Development

The thermostat behavior is described through a flowchart (Figure 10). The conditions are ordered in an overwrite hierarchy.

For the bandwidth thermostat, this is first evaluating whether the hourly price justifies heating. Then looking at current indoor temperature and determining where it falls in the bandwidth, adjusting heating based on these limits. Then the limit coasting is included; preventing the system from exiting bandwidth but allowing maintaining either limit if the price allows for it. An example is when at the bottom limit, but the hourly price happens to be unfavorable, in this case the system instructs to maintain lower bandwidth until prices decrease. Finally, edge cases are addressed, where indoor temperatures exceed bandwidth due to external factors. If the equations call for negative heating (cooling), heating is discontinued. To approximate human behavior, heating is disabled when outside temperatures reach 18°.

The fixed thermostat skips bandwidth logic, maintaining a set temperature. Its output is the resulting number from the heating equations. If external conditions drag it from its desired temperature, it is urged to return to it. If it is at its desired temperature, it maintains that temperature. Edge cases are addressed similarly, and heating stops above 18 degrees.

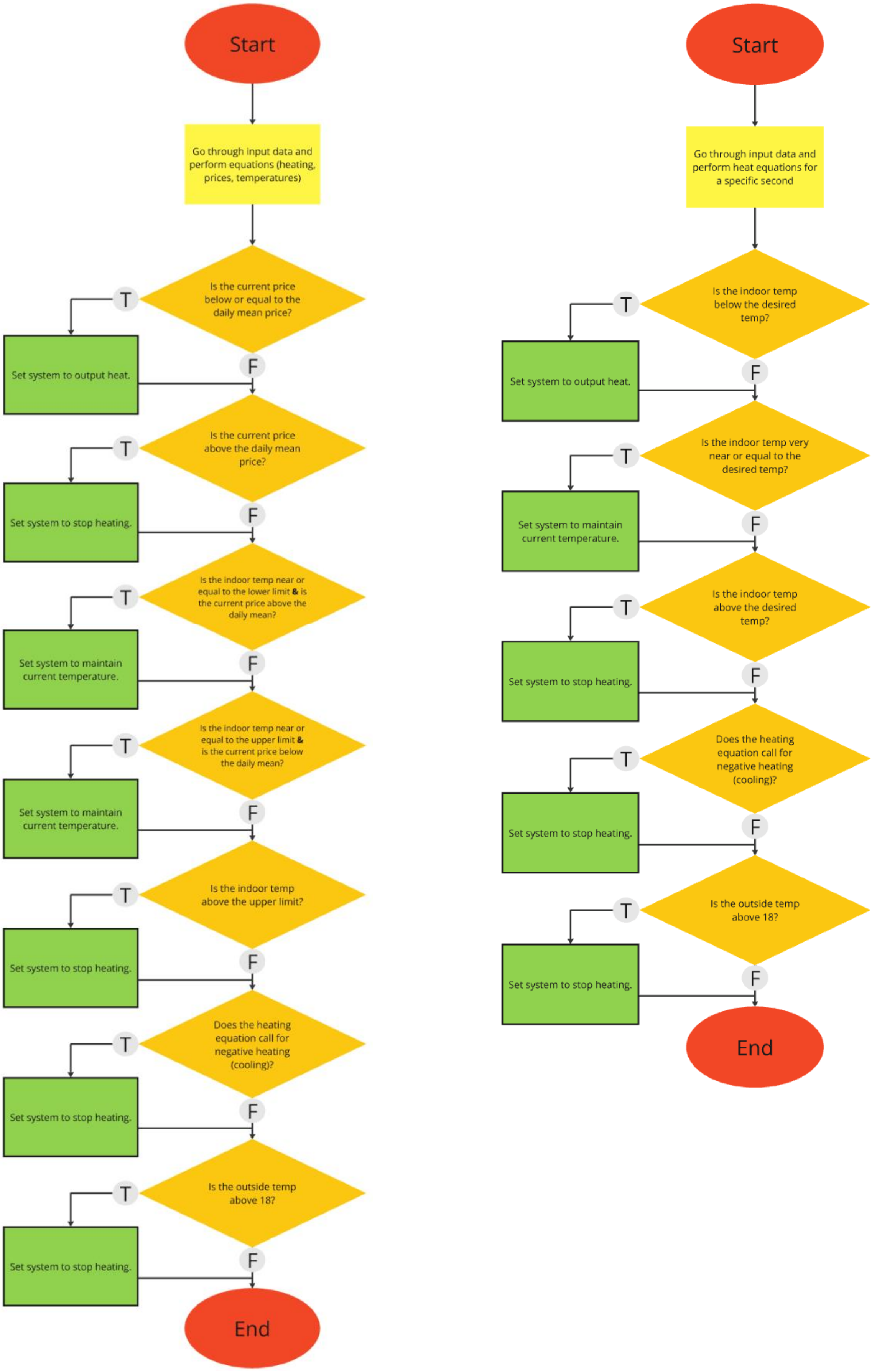


Figure 10: System heating logic of bandwidth thermostat, and comparative fixed thermostat

5.2 Context and Simulation Framework

These thermostats operate within a simulated framework. This is done by modelling a home, with a weather and energy price dataset. These are used in heat equations.

Home

An average Dutch home is sized to approximately 120m2 of living space (CBS, 2013). The approximate home featured in the code is a free-standing, two-story home. These characteristics represent homes in Loppersum. The model home features 12 windows, 2 doors and a flat roof. Its exterior dimensions are a 60m^2 footprint with the roofline at 5 meters height. These inputs factor into the heat equations due to their relative isolation values (Takkenkamp, 2024; Livios, 2024; Designingbuildings, 2023).

Weather

The average winter ground temperature is 4 degrees (Takkenkamp, n.d.), this represents most circumstances when heating is required. Weather data is registered by the KNMI (2024) across many weatherstations, data is extracted from station 280 – Eelde. This weatherstation is the closest to Loppersum. Weather data includes temperature data and solar radiation. Homes are often subject to shading by trees or other homes, assumed to be 20% in this simulation. Dataset cleaned and interpolated to match array sizes.

Energy Prices

Hourly day-ahead electricity price data is aggregated by Ember (2024) for European countries, updated monthly. The aggregated data is used for 2015 through 2024, a duration of 9 years. Dataset cleaned and multiplied to match array sizes.

Heating Equations

To determine heating characteristics, required output is determined through heating equations.

$$Q_{heating} + Q_{solarradiation} = Q_{ventilation} + Q_{conduction}$$

The other Q_{in} next to heating is heat from solar radiation. The losses of energy in homes are through radiation and ventilation.

$Q_{heating}$ is a resulting value from the equation. The thermostats can adjust this value, leading to an unbalance in the equation and resulting in temperature drifts.

$Q_{solarradiation}$ is a value taken from the KNMI Weatherstation Eelde. This value is a registered measurement, thus accounting for solar angle over the year is not necessary.

$Q_{ventilation}$ is a function that calculates heat loss due to mandatory ventilation laws in homes. It uses the specific heat capacity of air, the temperature difference between inside and outside and the mass flow rate.

$$Q = \dot{m} * c_p * \Delta T$$

Mass flow is 0.5 air changes per hour (ACH), this translates to 0.051 kg/s in this home.

$Q_{conduction}$ determines heat loss due to conduction. Isolation values of the various materials apply here, their surface area and real-time temperature difference. This function is executed for the following items: doors, windows, roof, floor, walls. For the floor, the temperature difference is calculated with ground temperature.

$$Q_{item} = (A_{item} * \Delta T)/(\frac{1}{U_{item}})$$

The resulting $Q_{conduction}$ adds these together to account for all conduction heat loss.

$$Q_{conduction} = Q_{door} + Q_{window} + Q_{roof} + Q_{floor} + Q_{wall}$$

Bandwidth Effect Comparison

To assess the impact of different bandwidths and accurately advise on best practice, three bandwidths are tested against the fixed thermostat. These bandwidths are ±0,5°, ±1° and ±2°. Their limits are within the comfortable ranges as indicated in research (Chapter 2). Results of this test can be used to suggest optimal user behavior.

Price-steering Mechanism Comparison

The bandwidth thermostat decides on optimal heating based on a pricing factor. It compares each hourly price to the daily mean price to decide its behavior. This allows for daily optimization, as energy prices can fluctuate between days. To adjust the heating behavior, a factor can be added to this mechanism. If the bandwidth thermostat is asked to compare hourly price to *daily mean price * 0,95* it restricts available hours where heating is favorable. In testing performance of the bandwidth thermostat using the steering metric based on hourly energy prices, three methods are compared. These are *strict*, *mean* and *lenient*. These are *mean * 0,95*, *mean* and *mean * 1,05* respectively. This seeks to discover whether price restriction influences performance.

Collaborative Heating

A method of introducing collaboration into HPDH is system-wide staggered heating. As homes are exposed to similar local climates and require similar heating, staggering their heating draw could supply the required heating while shaving peak demand. Lower demand peaks allow the MES to consist of fewer heat pumps. This is tested by copying a modelled home's heating requirement through time. Figure 11 shows a representation of this approach. This allows assessing if staggering decreases the maximum power draw of five homes, to less than the maximum power draw of five simultaneous homes which is *5 * 3000W*.

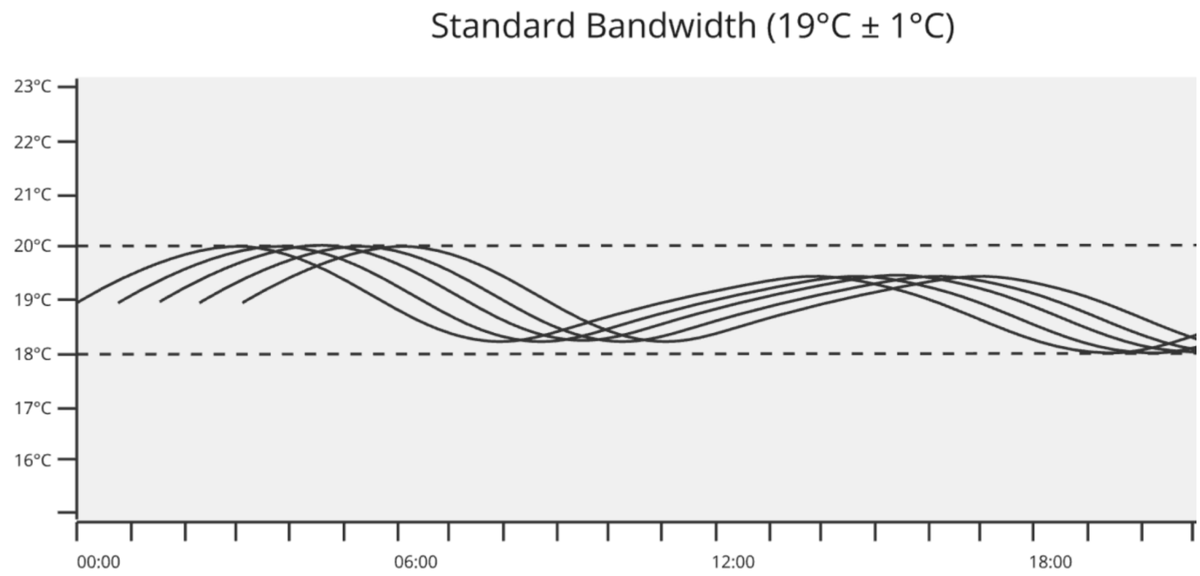


Figure 11: Simplified representation of staggering

5.3 Key Design Decisions

Cheap Energy

How the thermostat addresses current energy prices falls unto design decisions. As energy prices are unpredictable and can vary over weeks and years, the thermostat has been tuned to narrow its window. Energy prices are published day-ahead and vary by the hour. A 'cheap' price can only be determined in small windows of time, to prevent entire days being void of any heating. The current approach takes chunks of 24 hours from the pricing dataset, calculates the mean price for each day and compares each hourly price to the daily mean. This is a steering metric, where 'cheap' can be determined as a deviation from mean.

Simplifications

The fixed thermostat, to which the bandwidth is compared, is modelled to exactly solve the heat equation. This is a sufficiently accurate approximation within this simulation framework for comparison purposes.

Another simplification is approaching the home as a single thermal zone, where its values of insulation, ventilation and conduction are accurate but where temperature distribution is not spatially resolved. The entire home attains a completely uniform temperature, whereas realistically, spatial variations occur.

5.4 Testing and Validation

While testing the code performance, it is tested against one year of data at a time. For testing, data from 2020 is used. Different plots are assessed in visual inspection as a *sanity check*. Especially paying attention to the logical flow of seasons and accompanying expected heat equations, heating output behavior and bandwidth limits. Additional plots are visible in Appendix D.

Simulation

Figure 12 shows the output (W) of a heating system through either the bandwidth thermostat (Q_{out}) or the fixed thermostat ($Q_{maintain}$). For visual aid, the summer months have been highlighted. The most active period of the bandwidth thermostat coincides with the highest output of the fixed thermostat.

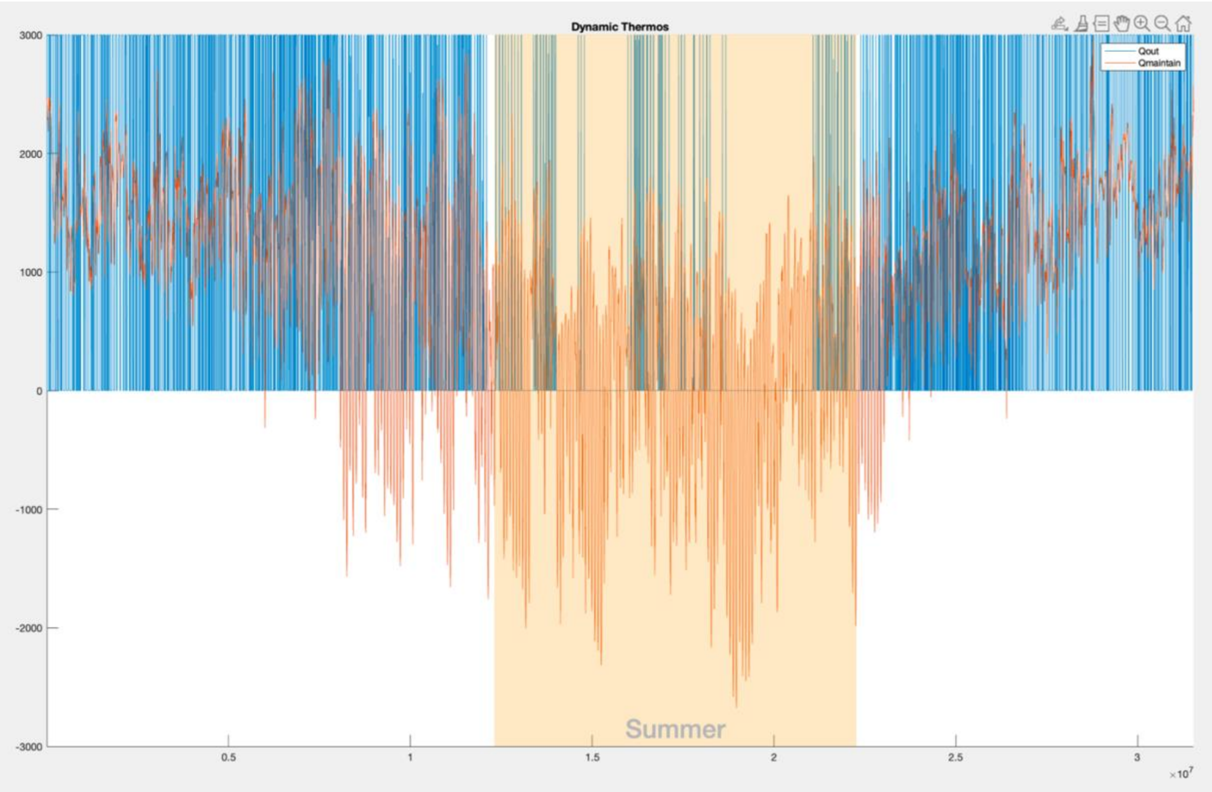


Figure 12: Heating output of thermostats over one year

Figure 13 shows the indoor temperature in bandwidth (°C), accompanied by outdoor temperature (°C). The indoor temperature does exit bandwidth in the summer, drawn out by high outdoor temperatures and the incapacity of the system to supply cooling. System performs as required and does not exit bandwidth.

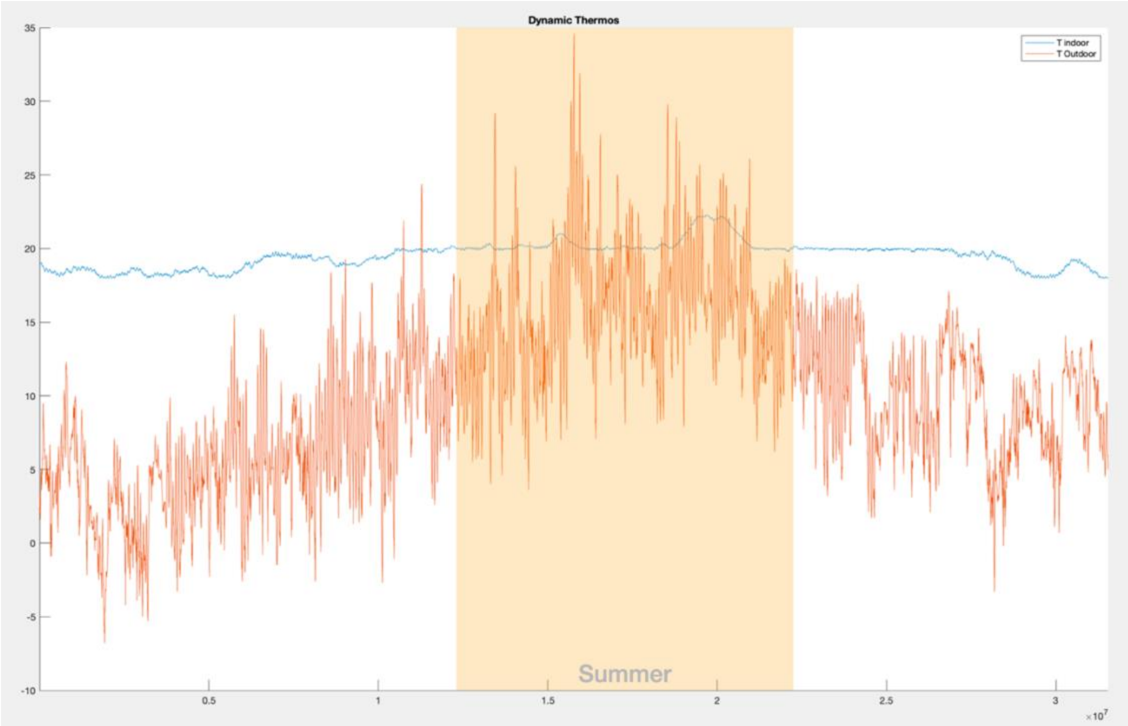


Figure 13: Indoor temperature plots over one year

Considering all factors in the heat equation, Figure 14 shows how these variables act over the year. The solar effect (W) in the heating equation peaks in the summer, where conduction and ventilation are less impactful due to higher outdoor temperatures.

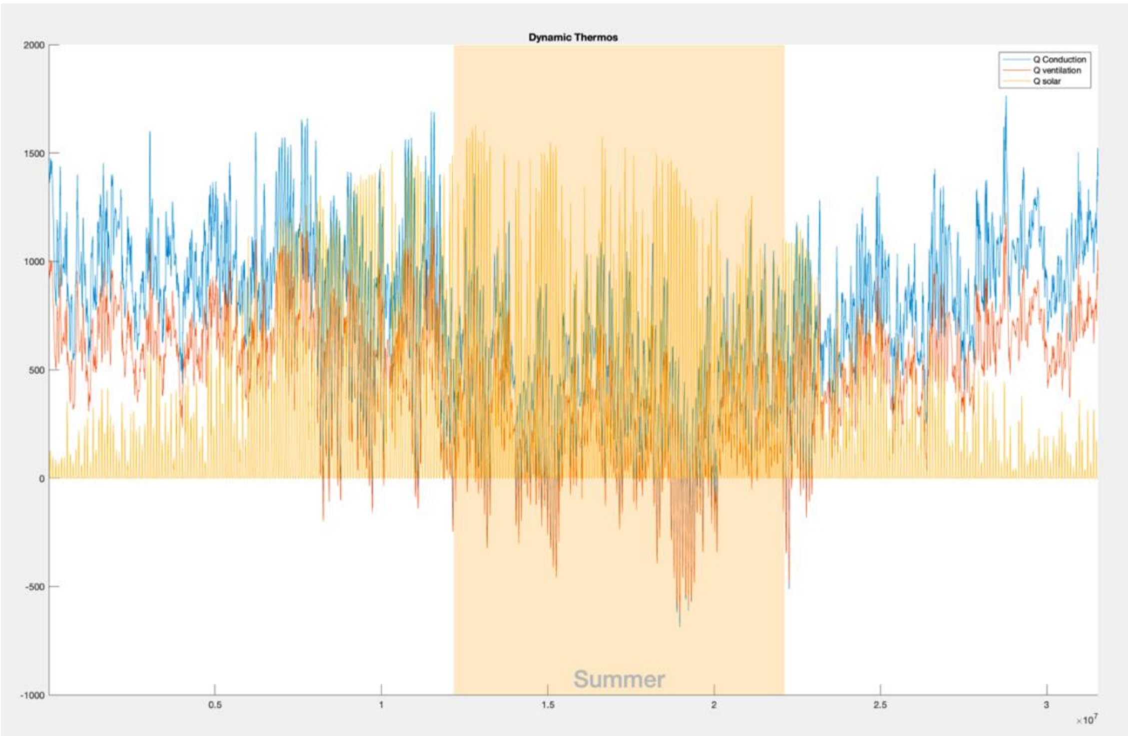


Figure 14: Heating equation input variables

These figures show no anomalies can be visually identified. Crosschecking with the data arrays indicates the same.

Bandwidth heating is tested against a fixed thermostat. Figure 15 reveals cumulative energy consumption (Wh). In its current state and within the constraints of this simulation, it is indicated that the bandwidth thermostat consumes **3,34%** more energy over the course of the year 2020.

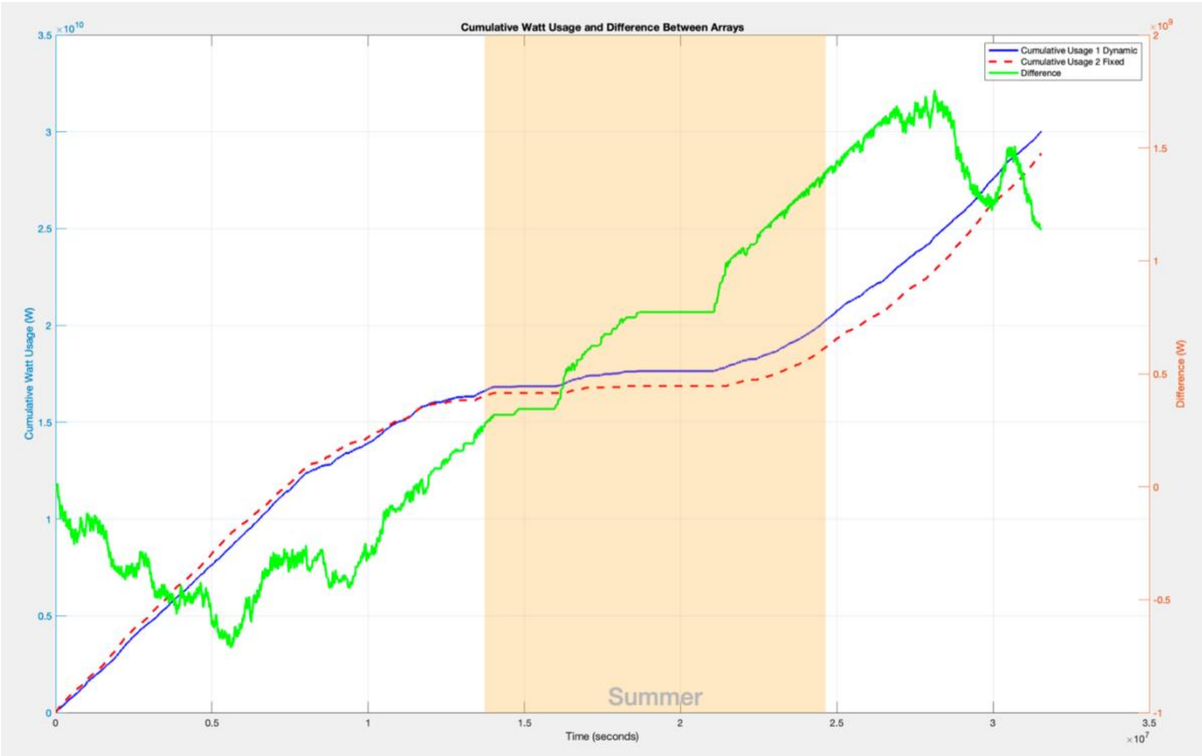


Figure 15: Bandwidth heating performance, energy consumption

Figure 16 indicates cumulative costs in €. In its current state and within the constraints of this simulation, it is indicated that the bandwidth thermostat is **17,7%** more economical over the course of the year 2020.

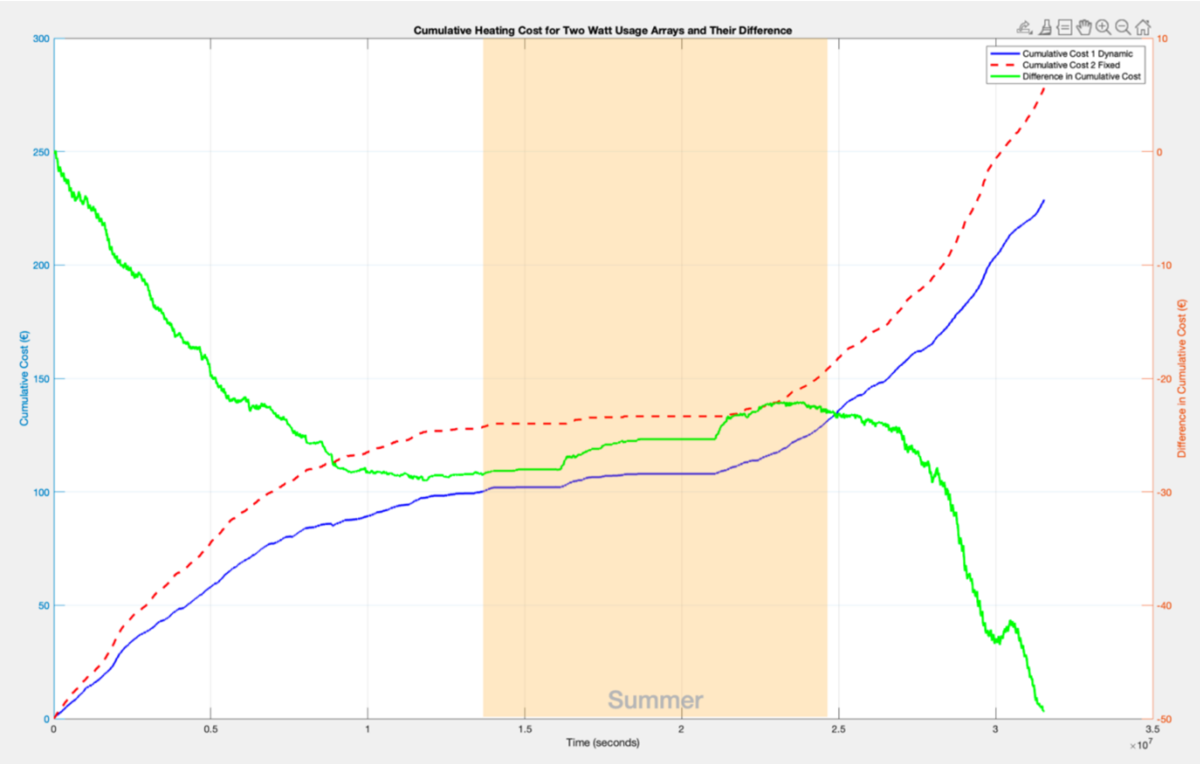


Figure 16: Bandwidth heating performance, cumulative costs

The performance over these two metrics is assessed over the years covered by both datasets, 2015 to 2024. Specific plots are visible in Appendix E, summarized in Table 3 describing the bandwidth performance relative to the fixed thermostat. These tests assume the bandwidth limits to be at 18° and 20°, with price-steering mechanism based on the mean daily price.

Table 3: Bandwidth performance in comparison to fixed thermostat

Year	**Cumulative Consumption**	**Cumulative Costs**
2015	+6,56%	-7,19%
2016	+2,63%	-9,72%
2017	+5,51%	-6,96%
2018	+2,32%	-8,91%
2019	+3,62%	-10,20%
2020	+3,34%	-17,75%
2021	+2,05%	-10,73%
2022	+0,81%	-17,59%
2023	+3,51%	-10,79%
2024	+7,38%	-5,56%

5.5 Results

Bandwidth Effect Comparison

The simulation runs each year and bandwidth adjustment separately, results are visible in Table 4. All are based on a target temperature of 19°C from which the bandwidth operates, with price-steering mechanism based on the mean daily price. Percentage differences are compared to a fixed temperature thermostat (Figure 10, right). All bandwidths perform every year in a more cost-effective and a more consumptive manner than the fixed thermostat they are compared to, except the ±2° bandwidth loses its cost advantage in 2024. The ±1° bandwidth produces highest average savings, the ±0,5° bandwidth produces lowest average consumption increase. The ±2° underperforms in all years.

Table 4: Bandwidth performance, bandwidth size variable

Year	**Bandwidth ±1°**		**Bandwidth ±2°**		**Bandwidth ±0,5°**	
	Consume	***Cost***	***Consume***	***Cost***	***Consume***	***Cost***
2015	+6,56%	-7,19%	+12,87%	-3,28%	+3,08%	-9,76%
2016	+2,63%	-9,72%	+5,96%	-9,11%	+1,38%	-9,32%
2017	+5,51%	-6,96%	+12,16%	-3,35%	+2,68%	-7,69%
2018	+2,32%	-8,91%	+6,12%	-7,52%	+1,19%	-8,32%
2019	+3,62%	-10,20%	+7,44%	-9,83%	+1,75%	-10,31%
2020	+3,34%	-17,75%	+8,69%	-16,75%	+1,94%	-16,94%
2021	+2,05%	-10,73%	+5,08%	-10,68%	+1,03%	-10,29%
2022	+0,81%	-17,59%	+2,39%	-12,34%	+0,88%	-10,06%
2023	+3,51%	-10,79%	+6,79%	-10,52%	+1,52%	-10,61%
2024	+7,38%	-5,56%	+17,04%	+0,89%	+3,39%	-7,62%
Average	+3,77%	-10,54%	+8,45%	-8,25%	+1,88%	-10,09%

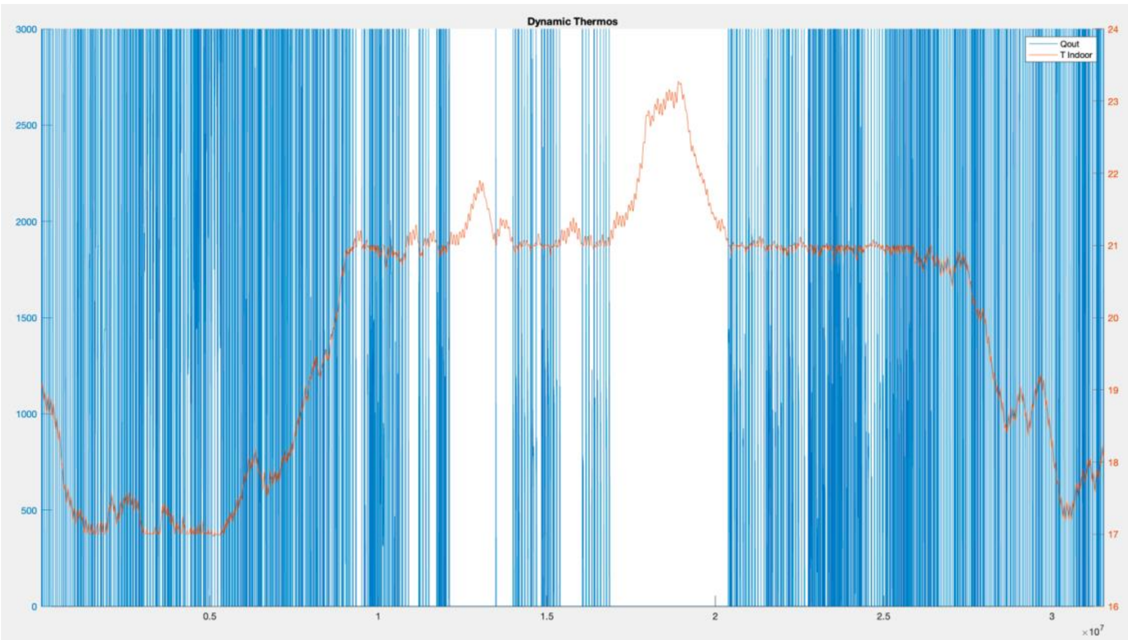


Figure 17: Indoor temperatures and heating output, BW±2, 2018

Figure 17 depicts T_{indoor} of 2018 circumstances, with a Bandwidth ±2°. Broader bandwidths are prone to limit riding.

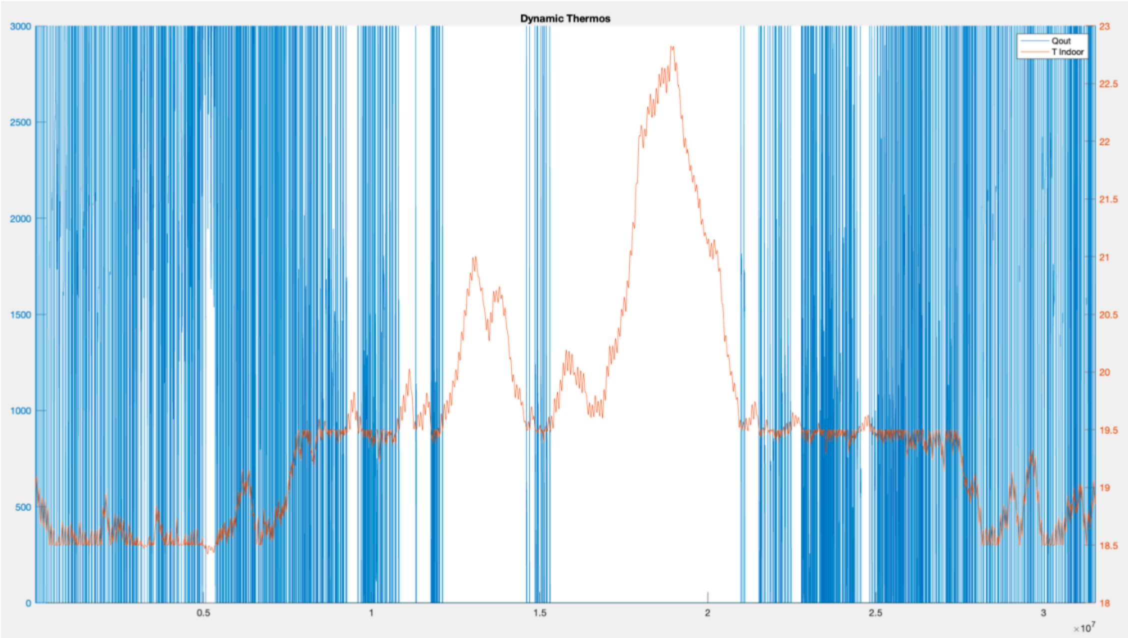


Figure 18: Indoor temperatures and heating output, BW±0,5, 2018

Figure 18 depicts T_{indoor} in 2018 circumstances, with a Bandwidth ±0,5°. Similar limit riding is visible, though restricted by the narrow bandwidth.

Price-steering Mechanism Comparison

In code development, a mechanism of assuming the daily mean price to decide on heating behavior produced an acceptable heating characteristic where both limits of the bandwidth were reached. The price-steering mechanism test reveals behavior changes. Table 5 shows the results from the testing. They are all based on a target temperature of 19°C with a bandwidth of ±1°C, allowing between 18° and 20°. This is best practice from bandwidth testing.

Table 5: Bandwidth performance, price-steering variable

Year	**Mean Steering**		**Lenient Steering (1.05)**		**Strict Steering (0.95)**	
	Consume	***Cost***	***Consume***	***Cost***	***Consume***	***Cost***
2015	+6,56%	-7,19%	+10,08%	-2,04%	+0,75%	-13,13%
2016	+2,63%	-9,72%	+6,06%	-5,42%	-0,39%	-11,88%
2017	+5,51%	-6,96%	+7,71	-3,59%	+3,00%	-9,16%
2018	+2,32%	-8,91%	+5,85%	-4,09%	-0,54%	-10,74%
2019	+3,62%	-10,20%	+7,20%	-5,95%	-1,56%	-12,86%
2020	+3,34%	-17,75%	+8,70%	-12,70%	-0,01%	-19,83%
2021	+2,05%	-10,73%	+5,77%	-6,95%	-1,15%	-12,85%
2022	+0,81%	-17,59%	+7,21%	-5,83%	-1,99%	-12,49%
2023	+3,51%	-10,79%	+7,72%	-6,79%	-2,42%	-13,21%
2024	+7,38%	-5,56%	+10,28%	-1,44%	+2,93%	-11,09%
Average	+3,77%	-10,54%	+7,66%	-5,48%	-0,14%	-12,72%

When steering in a *lenient* mechanism the temperature drifts towards upper ends of the bandwidth with an average temperature of above 19° (Figure 19). It remains less expensive than a fixed thermostat at 19°.

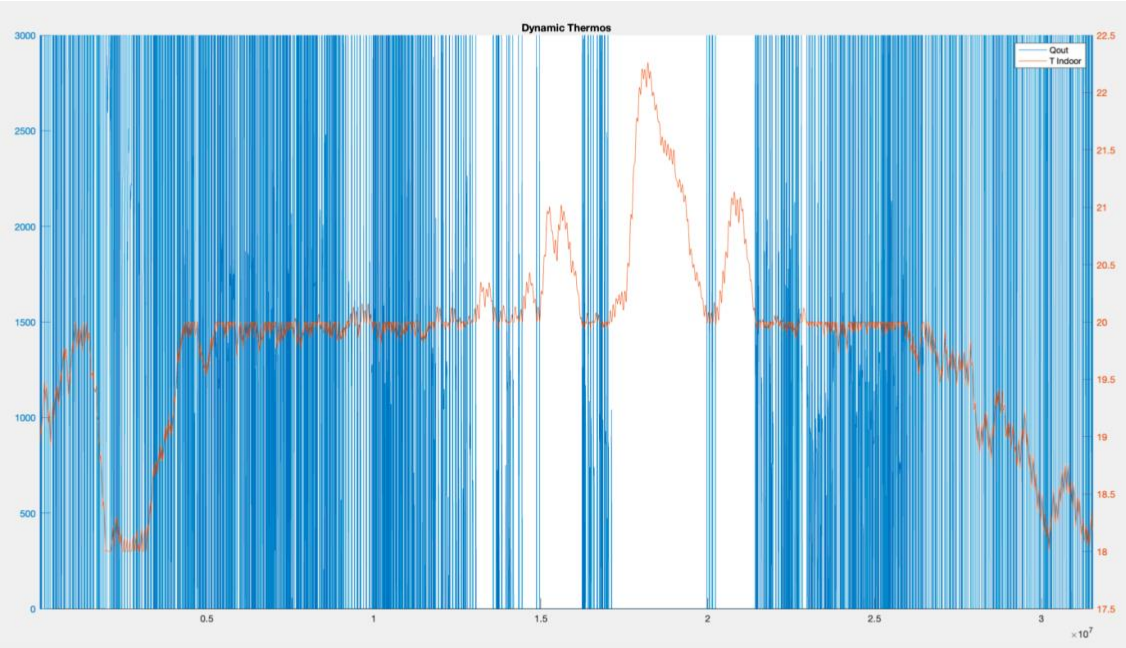


Figure 19: Indoor temperatures and heating output, BW±1, lenient, 2016

When restricting the price-steering the temperature drifts towards the lower limit of bandwidth (Figure 20).

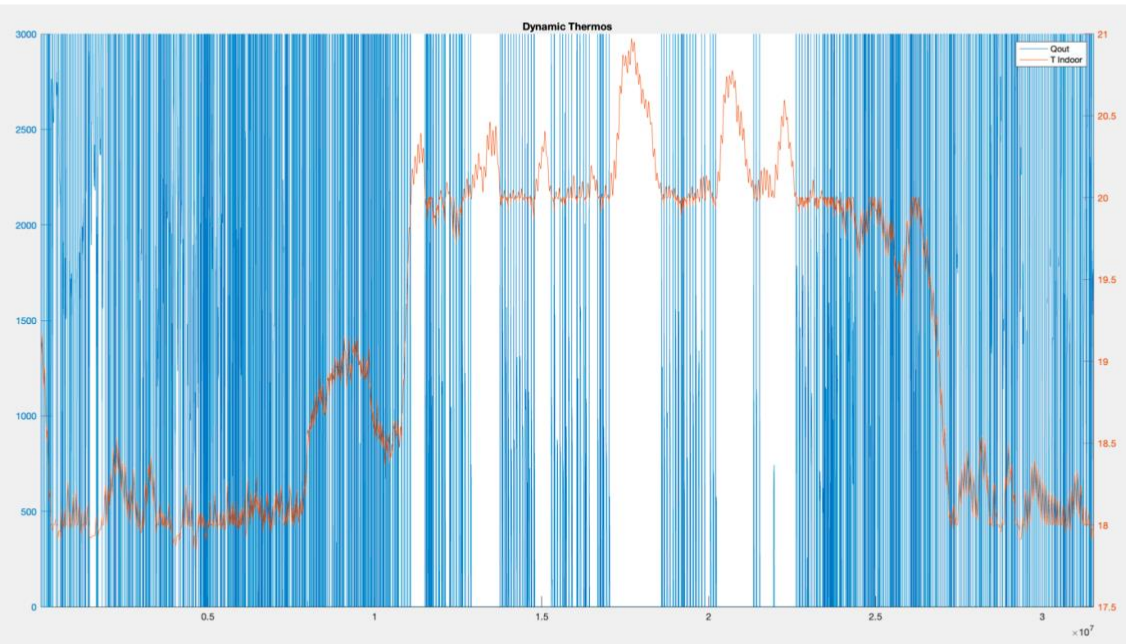


Figure 20: Indoor temperatures and heating output, BW±1, strict, 2016

All steering mechanisms perform every year in a more cost-effective manner than the fixed thermostat they are compared to. The *strict* mechanism outperforms by reducing consumption while maintaining the largest cost reductions. The *mean* mechanism

(Figure 21) follows the characteristics of a bandwidth system with less limit riding. As emphasis lay on cost-effective and less consumptive heating, the *strict* mechanism performs well. The lenient mechanism underperforms.

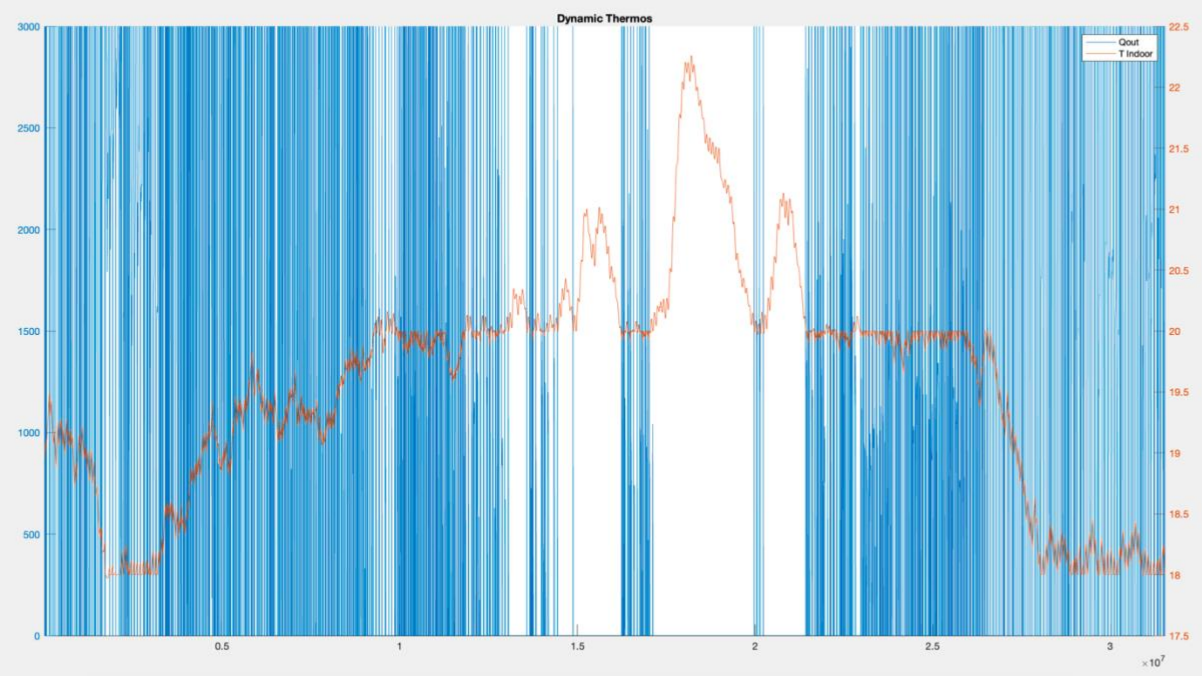


Figure 21: Indoor temperatures and heating output, BW±1, mean, 2016

Consumption Division Sustainability Comparison

As per Cacciarelli et al. (2025), there is evidence that influxes of renewable energy impact electricity pricing. While market conditions vary, findings suggest that wind and solar generation generally exert downward pressure on prices. Moreover, this price-reducing effect has become more pronounced over time, highlighting the growing influence of renewables in electricity markets.

Most simulated variations of bandwidth heating show increased consumption in comparison to a fixed thermostat. Their consumption patterns favor cheaper energy, which may indicate a more sustainable solution while providing a method to integrate renewable energy into the grid. Figure 22 shows yearly consumed energy (Wh) in 2020, cumulative for both a bandwidth and fixed thermostat, divided over 'cheap' and 'expensive'. This division is made based on daily means.
It is evident that bandwidth heating prioritizes the hours in which the grid is more likely to consist of a greater share of renewable energy, consisting of 96% cheap energy, opposed to 51% with the fixed thermostat.

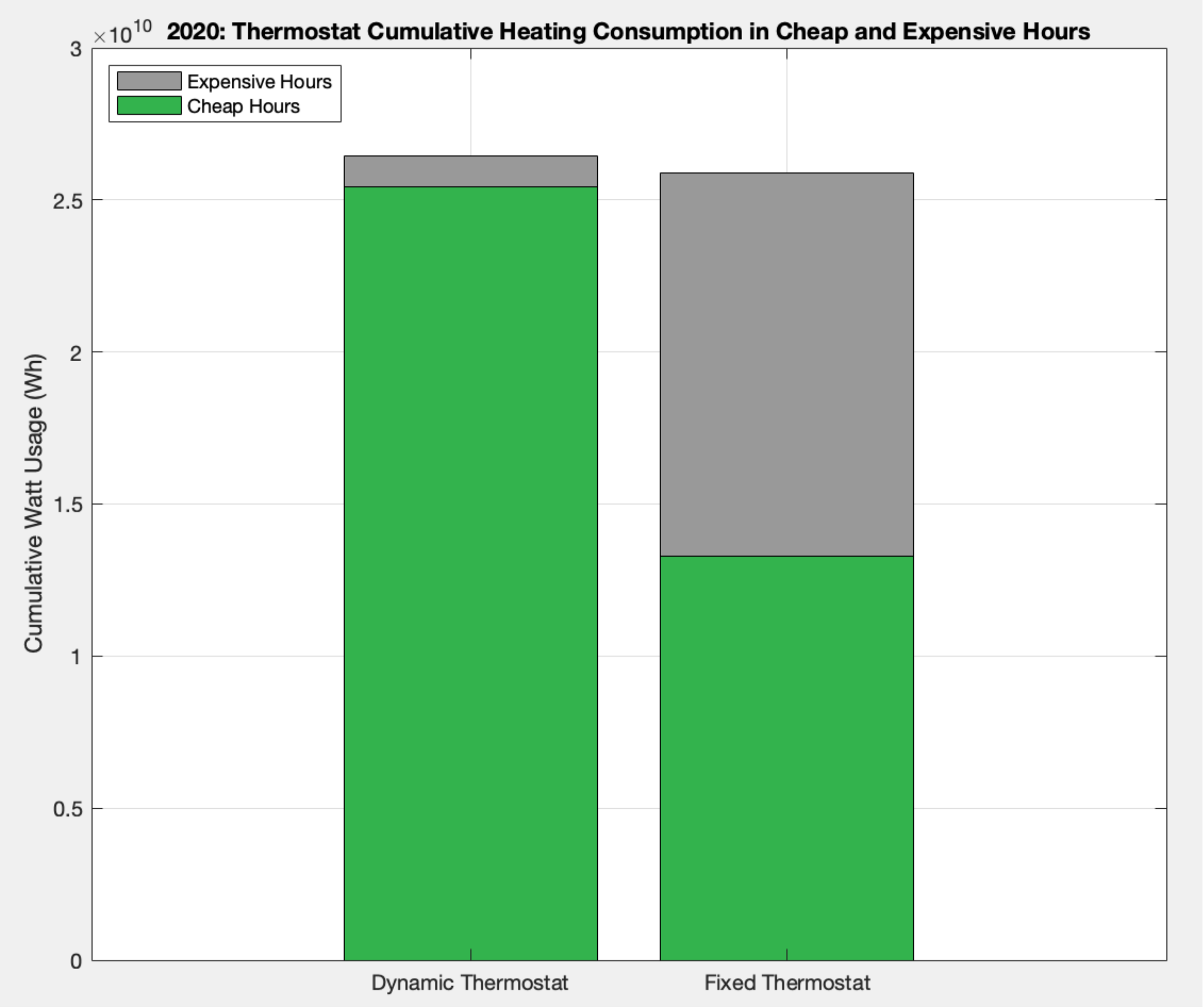


Figure 22: Cumulative consumption for bandwidth and fixed thermostat, divided over cheap and expensive

Collaborative Heating

Testing graphs reveal spacing demand of five homes based on shifting demand through time by one hour, within the current simulation does not decrease peak consumption. Due to some demand peaks lasting many hours, any staggering still overlaps in maximum demand. Figure 23 shows the bandwidth draws maximum power for 12 hours, from the selected point. This is one of many instances. Within this timeframe, maximum combined power draw of staggered homes match non-staggered homes.

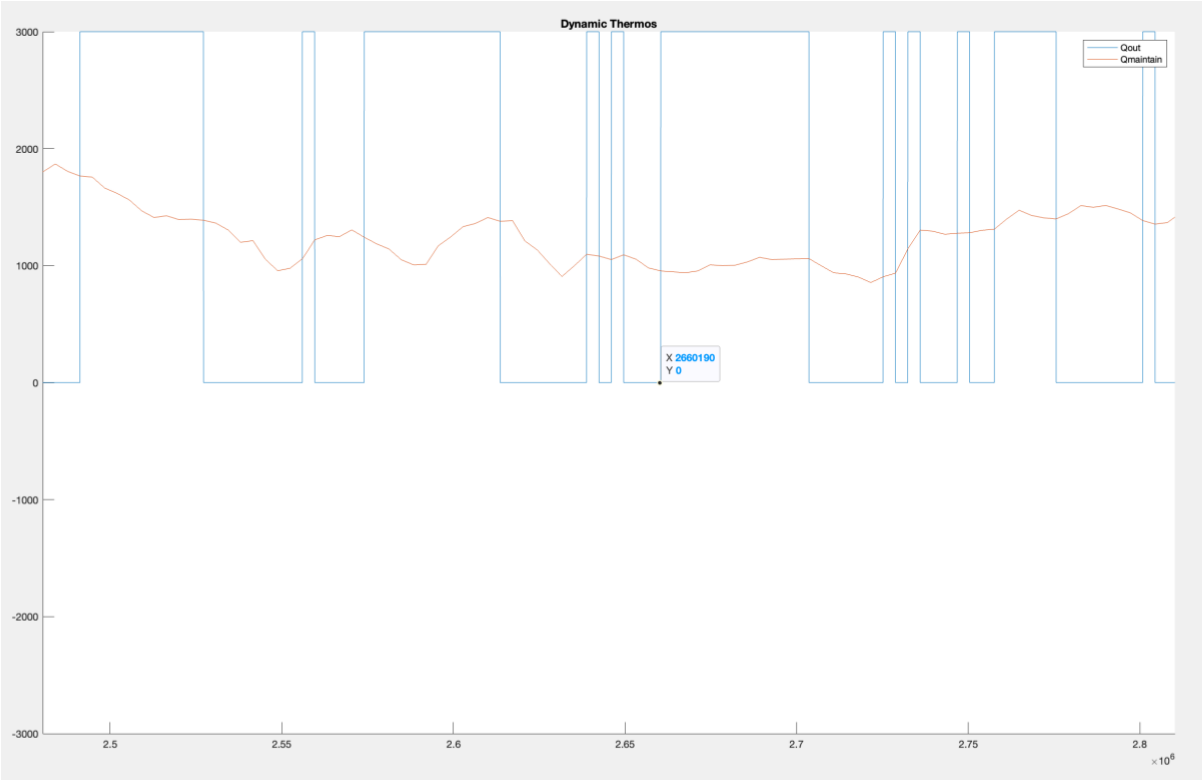


Figure 23: Bandwidth heating consumption, BW±1, 2018

5.6 Discussion and Design Implications

The bandwidth thermostat demonstrates its ability to regulate heating between bandwidth limits while prioritizing economical heating. This proof-of-concept proves an effective approach to model and implement bandwidth thermostat behavior. The integration of realistic datasets and parameters contributes to the validity of these findings. This research aims to address two hypotheses in validating and optimizing bandwidth heating. Results from this research aid in concept validation and defining key challenges and opportunities for further development.

The results indicate that the first hypothesis 'The larger a bandwidth range is, the more economical it will heat, with consumption remaining near-equal' is disproven. Instead, findings suggest that larger bandwidths can lead to higher overall consumption and less economical heating. This challenges the initial assumption that greater flexibility would always result in lower costs. These results are influenced by the current state of bandwidth heating in the simulation where limit riding is prevalent, and greater bandwidths allow a higher temperature resulting in greater consumption. Figure 16 reveals how indoor temperatures are riding the upper limit for large portions of time, in turn driving consumption and costs. Through refining the bandwidth behavior to account for external factors such as outdoor temperatures limit riding could be decreased and the competitiveness of larger bandwidths likewise. Additionally, adjusting thermostat behavior based on indoor temperatures being above or below the target temperature could ensure limit riding is decreased.

A rudimentary approach is to test the 19° ±2° bandwidth at strict price steering, but restricting heating to below 20°. This results in a 2019 consumption of -1,31% and costing -14,53%. Best practice from testing is the 19° ±1° bandwidth at strict price steering consuming -1,56% and costing -12,86% compared to a fixed thermostat. This approach makes the larger bandwidth more competitive.
Though testing ultimately disproves the larger bandwidths efficacy, bandwidth driven heating does decrease costs and can maintain near-equal consumption. With further refinement of bandwidth behavior this hypothesis could be proven.

The second hypothesis 'Collaborative heating can be achieved by staggered heating to induce peak demand shaving' is disproven. Testing shows that staggered heating, as implemented in this simulation, does not effectively reduce peak demand.
The assumption was that by staggering heating times across users, overall demand peaks could be reduced. However, findings suggest that staggered heating merely redistributes consumption, with longer demand peaks overlap in consumption. In its current form, the system lacks mechanisms to anticipate and react to broader demand patterns, leading to delayed but equally intense peaks rather than true load reduction.
These results highlight a key limitation in the current approach: effective peak shaving likely requires a more adaptive coordination strategy, where heating schedules are dynamically adjusted based on real-time grid conditions rather than pre-set staggering.
Further development could explore integrating predictive demand algorithms or introducing incentives for users to adjust heating behavior collaboratively.
While the tested implementation of staggered heating does not achieve demand shaving, it reinforces the need for more sophisticated coordination in collaborative heating models.

Limitations - The testing proves the efficacy of this theoretical concept, in further development more parameters, functions and dependencies are required for optimization and refinement. This will allow the bandwidth to alter its behavior based on the input data. Where this concept attains a bandwidth on a day-to-day basis, better optimization may induce more economical heating by comparing day-means and using weather forecasts to come to reach higher-level functioning.
Another limitation is using visual inspection to validate, which introduces subjectivity and potential oversight in identification. A more rigorous validation method could improve accuracy of bandwidth assessment.
The current simulation does not account for user interference, or other real-world effects such as occupancy patterns, variations in building insulation and heat distribution efficiencies. In moving past a conceptual state these limitations are to be addressed.
Lastly, user comfort is assumed without explicit validation. Literature confirms bandwidths to be acceptable and grants insight into temperature drifts and ranges, but real-world feedback allows finetuning acceptability and in turn desirability.

Recommendations - To improve bandwidth heating, refining thermostat behavior to account for outdoor temperatures and price fluctuations can reduce limit riding and improve performance. Adaptive constraints should be explored to revisit bandwidth size impacts on consumption and costs.
For collaborative peak demand shaving, real-time demand forecasting and adaptive scheduling are preferred over static staggering. An interdependent approach could reveal opportunities for peak shaving.
Future development must refine the steering mechanism to incorporate external factors, as well as balance it against the target temperature to reduce limit riding. Additionally, real-world factors like insulation, occupancy patterns, and user feedback will enhance accuracy. Shifting from visual validation to quantitative methods will improve reliability.

Influence on Interface - The results from code development prove bandwidth heating is a valid approach to reducing heating costs. The method relies on frequent switching between drawing heat and coasting from HPDH, and this behavior requires clear communication to users on why and when heating is activated or disabled. This conceptual proof relies on preventing user interference, already a core principle of interface development. Controls given to users must cover overarching functionalities, such as adjusting a subscription to a different bandwidth, rather than granting easy control over finetuning desired temperatures or instant demand.

Chapter 6: Digital Interface Development

6.1 Introduction

PURPOSE

There is no existing interface standard for bandwidth heating. Understanding how users interact with it is crucial for adoption. Users may struggle to grasp the concept, which impacts bandwidth performance. Likewise, user interference and behavior is a metric to account for in further development of bandwidth heating. This development of an interface builds upon the questions 'How do users interact with bandwidth heating, and what factors influence their ability to set it effectively?' and 'Do users intuitively understand and apply the concept of bandwidth heating when making heating decisions?'. The hypothesis is 'Users will correctly adjust their bandwidth based on cost and comfort considerations, while attaining their desired temperature.'. The objective in this research is to ideate and develop an interface, and to test if users understand and engage with bandwidth heating in a way that aligns with economical and less-consumptive goals.

6.2 Iterative Approach

Understanding user behavior requires iterative refinement to eliminate interface bias and focus on bandwidth comprehension; it is aimed to research user comprehension rather than interface quality. A sufficient interface is required to not hamper user understanding. Through user feedback loops, morphological charts and an A/B-test, all visible in Appendix G, the interface to test the hypotheses is created.

A notable outcome of this method produced the HaaS-avatar (Figure 24), which serves as a visual representation of the current system state such as *heating* or *coasting*. It aims to distill system behavior into a recognizable form.

Figure 24: Avatar system representations

The paper prototype (Figure 25) now includes a home screen with an avatar showing system status. A sleeping avatar indicates no heating. Temperature adjustments are made through a separate screen with a bandwidth-button. Additional screens provide insights on costs, and collaborative measures to encourage desired behavior.

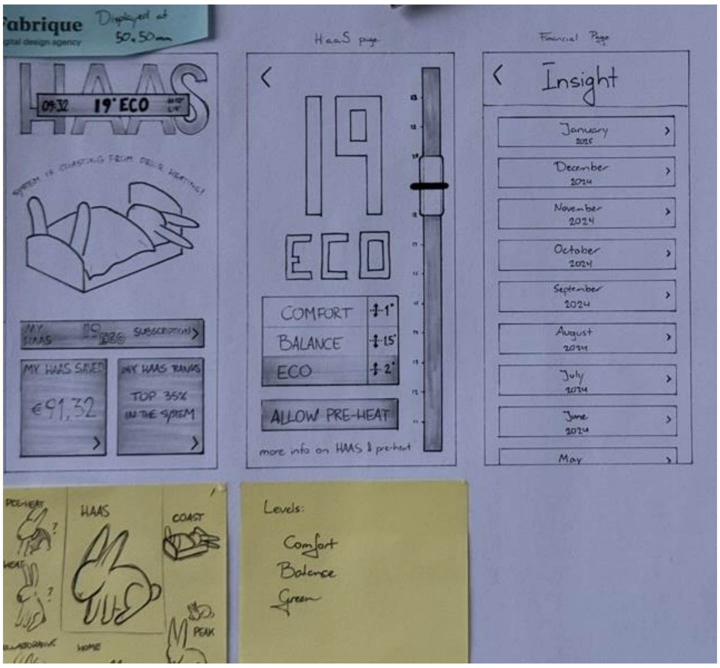


Figure 25: A/B-test paper prototype

6.3 Testing Desired Interface Hosting Device

A key uncertainty emerged on whether user preference lay with a conventional wall-mounted interface or rather with a mobile application. This distinction carries implications for user behavior. An A/B-test reveals this preference, full details are visible in Appendix H.

Within the test eight participants of varying ages, self-rating their tech proficiency (Table 6), are exposed to the concept interface in the capacity of an application (Group A) or wall-mounted interface (Group B). Participants are asked to perform tasks within this interface, such as adjusting temperatures, determine system status and explaining their thought process in follow-up questions.

Table 6: A/B-test participant list

ID	Age	Interface	Tech Proficiency
P1	23	A	High
P2	27	A	Medium
P3	31	A	High

P4	74	A	Medium
P5	67	B	Low
P6	24	B	High
P7	30	B	Medium
P8	59	B	High

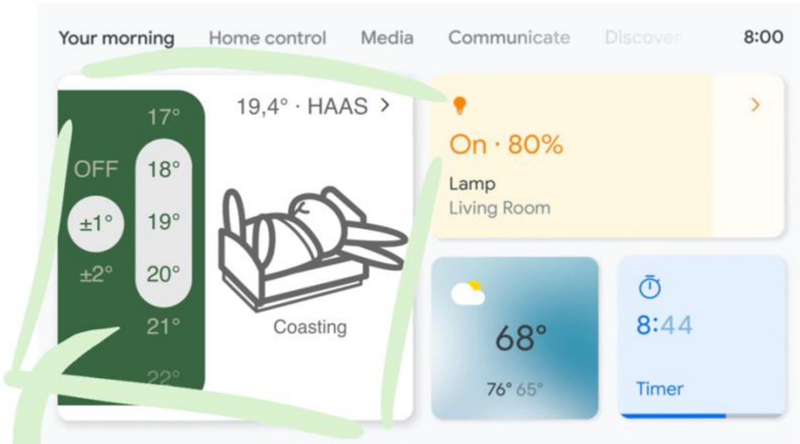
FINDINGS

Findings indicate a slight user preference towards the conventional wall-mounted interface, with phone integration advisable in further interface development. It is possible this test does not represent the larger population of users, as development progresses further testing is recommended. Group B participants note a familiar and intuitive interface, the minimal interaction less so. Both groups remark the avatar to be useful, but not clear in itself. Button labels are misunderstood, in turn decreasing bandwidth understanding. Collaborative measures are unclear. Highly tech-proficient users appreciate the system requiring minimal attention in its operation.

6.4 Digital Concept Development

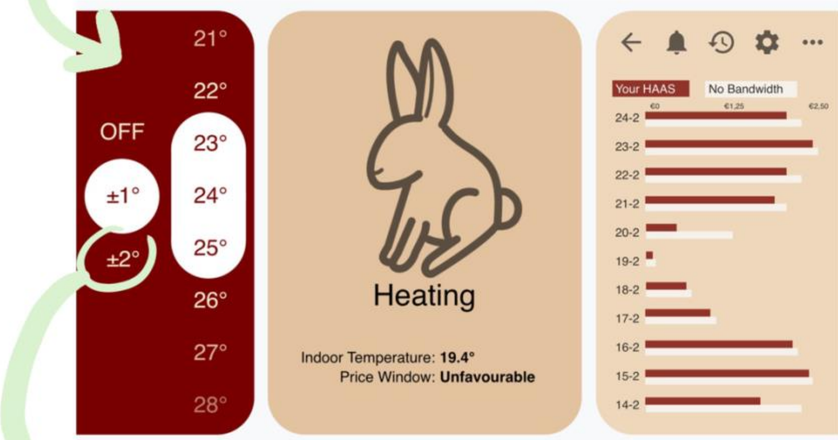
Results from the A/B-test are incorporated into further digital prototyping (Appendix I). This creates a testable concept. As results point towards a wall-mounted device, digital prototyping had this direction. Rather than creating a new dedicated product, an existing host is assumed as the foundation for interface development. For Alliander this is a more realistic method of implementing bandwidth heating than creating a dedicated product. This is the Google Nest Hub (Figure 26), for which a bandwidth heating widget is created. In this phase, background API compatibility and other technical limitations are out of scope. The focus lays on how users interpret and interact with bandwidth heating through this interface. Building in Protopie allows embedding of interactions, enhancing the credibility in testing.

Figure 26: Example of interface hosting device: Google Nest Hub



The widget for the bandwidth heating system within the Google Nest Hub interface. It displays system status through a captioned avatar, current indoor temperature and bandwidth settings. No controls are available in this overview.

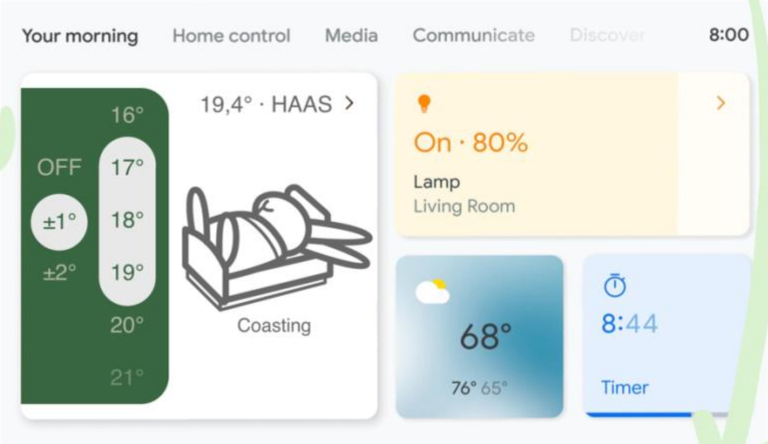
Tapping the widget leads a user to the home screen. Widget information is displayed here, now as an interactable button to set bandwidth and target temperature. In this view, the right-most window is a changeable display for different menus. This figure shows a bandwidth performance graph. This aims to increase understanding of the system.



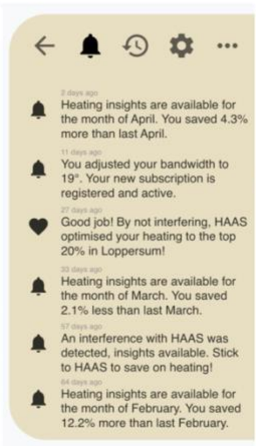
Upon adjusting the bandwidth above the current indoor temperature, the screen adjusts to a heating mode. This is accompanied by a different avatar.

Upon adjusting the bandwidth range, an indicator behind the temperature dial changes size to accommodate the selected temperature range.

Upon deactivating the bandwidth, the indicator narrows to only the selected temperature. The avatar displays inactivity of bandwidth.



All adjustments are visible in the widget on the home screen of the hosting device.



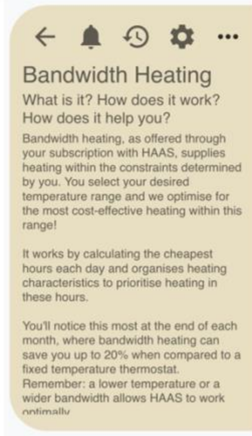
The window adjusts to different menus when tapping an associated icon.

The notification tab displays updates, as well as informing the user on consequences of their interference.

The avatar states tab shows the available avatars and what they convey, the menu serves as an explanation to unfamiliar users.

The cost insights tab shows monthly billing and cost consistency. The makeup of their bill and how bandwidth has compared to a fixed thermostat.

The window displays extended information on bandwidth. For those unfamiliar, unsure or confused this window explains the principles of bandwidth heating and best practice.



6.5 Digital Prototype User Testing

PURPOSE

This method is structured to assess how users interact with bandwidth heating, how they set it and whether they intuitively understand its principles when making heating decisions. The research questions are 'How do users interact with bandwidth heating, and what factors influence their ability to set it effectively?' and 'Do users intuitively understand and apply the concept of bandwidth heating when making heating decisions?'. The hypothesis is 'Users will correctly adjust their bandwidth based on cost and comfort considerations, while attaining their desired temperature.'.
Test objective is to determine whether users understand bandwidth heating without prior explanation, and how users adjust bandwidth settings. Answers are translated, refined to concise sentences which are approved by the participant.

Participants

Participants are invited through acquaintance and a previous survey pool. Test participants are at least 18 years old, other demographics are varied. No other requirements are included as heating systems have a broad customer base. The sample size is 12 participants (Table 7) from which qualitative insights are gathered through observation and a post-test survey. This is registered to discover if it affects understanding.

Table 7: Interface testing participant list

ID	Age	Tech Proficiency
P1	27	Medium
P2	24	Low-Medium
P3	25	Medium
P4	67	Low
P5	74	Medium
P6	25	Medium
P7	27	Medium
P8	54	High
P9	31	Medium
P10	58	Low

Test Setup

Interface: The Google Nest Hub interface prototype, displayed on a laptop screen. Interacting facilitated with a computer mouse.

Observation: Insights captured on user behavior through an observation sheet and a post-test survey (Appendix J).

Procedure

Users are not supplied with prior explanation, rather a minute is granted to create familiarity. Next the participant is asked: "What do you think this interface does?". This question aims to address intuitive understanding, without directly addressing the avatar.

Next users are requested to complete three tasks, under a think-aloud protocol. After each task a participant is asked about the effects of this task on the heating system. Observations are noted.

Task 1: You just moved into a new home with this heating system. Set up the system to your preference, considering all parameters.
Task 2: Generally, you like the temperature of your home, but tonight you feel just a bit too cold. What do you do?
Task 3: You are going on a vacation for one month. What do you instruct your heating system to do in this time?
Task 4: You want to reduce your heating bill, without compromising on comfort. What do you do?

The post-test survey consists of qualitative and quantitative questions, to gain understanding of participant behavior.

1. How did you decide on your bandwidth settings?
2. Did you feel in control over your heating? Why or why not?
3. What was not clear about bandwidth heating adjustments?
4. Would you trust this system to optimize heating for you?
5. Was there a moment where you felt confused? What caused it?
6. Would you be open to using such a system in your life?

The following statements are rated from 1 to 10, where users indicate their agreement.

1. The system is intuitive.
2. The system avatar is intuitive.
3. I feel confident using this system and understand how it works.
4. I agree with bandwidth heating hovering around my desired temperature if I save money.
5. I trust this system to not require my intervention.

6.6 Results

Participant data is collected through the observation sheet, all sheets visible in Appendix J. Participants are not visually or audibly recorded in testing.

Participants agree with reducing heating costs and that bandwidth is an acceptable solution for it. Participants note accepting fluctuation in temperatures, P8: ***"…I don't think I would notice 1° of difference really"***. Some participants relate to their own heating practices in their home, and state reaching for a sweater before adjusting the thermostat, P2: "***I would just look for a sweater***".

Automation is welcome, participants appreciate a set-it-and-forget-it approach, P6: "***I like that it does not require my attention, I am not very interested in heating***". They are not interested in heating systems and automation appeals to them. As this system offers some automation, it seems more is expected of it and many participants question whether other functions could be automated as well, such as a vacation mode where the system optimizes it and the user can trust it is being handled, P6: "***I would like a vacation button, so the system automatically adjusts***".

Bandwidth understanding varies and some want more feedback, P8: "***I would like some feedback on my actions, what does bandwidth do for me***", while others state being unsure about how their settings affect savings and comfort, P7: "***I don't see the direct influence of my choices***".

The wider ±2° bandwidth sparked thoughts of being too uncomfortable, even though it may be cheaper, P1: "***Two degrees off target does seem too much for my comfort***". The most chosen bandwidth in setup is ±1°. Participants said to consider comfort and costs in their selections and made use of the bandwidth in all scenarios.

Some participants feel unfamiliar and are hesitant with the interface, where others are keener to learn-by-doing and press all the buttons to find out what they do. These different participant-types influence how a person discovers the system.

Participant ratings of statements are aggregated in Table 8. Though values differ between participants, it is visible that the concept of bandwidth heating is generally agreed upon: some fluctuation is acceptable if it decreases costs. The first two statements pertain to the quality of the interface. The third statement set out to test user confidence in bandwidth heating, in testing these ratings were heavily influenced by interface ratings.

Table 8: Interface testing participant Likert ratings

ID	*1. The system is intuitive*	*2. The avatar is intuitive*	*3. I feel confident using the system*	*4. I agree with bandwidth*	*5. I trust the system to not require my intervention*
P1	7	7	5	9	6

P2	4	5	3	9	6
P3	8	8	8	6	8
P4	5	6	3	8	5
P5	8	4	9	7	6
P6	9	7	9	8	10
P7	3	6	6	7	7
P8	8	6	7	9	6
P9	6	6	5	9	7
P10	3	5	5	9	6
Avg	6,1	6,0	5,5	8,1	6,7

Key Takeaways for Design

This is the resulting advice for a concept iteration, to improve it according to user feedback. Improvements visible in Chapter 8.

1. **Impact and Comparison** - Participants want to see impact of their choices, and clear effects and comparisons between the choices they have.
2. **First Time Tutorial** - UI elements can be improved, as well as some participants inquiring about an introductory tutorial in the interface.
3. **Bandwidth Understanding** - The bandwidth is understood, this ranges from superficial to deeper grasping how price fluctuations dictate heating behavior. More detailed explanation or dynamic visual cues may enhance understanding.
4. **Avatar Clarity** - The avatar is liked, though it is not always directly linked to the system status and seen more as a placeholder. This leads to confusion.
5. **Optimization Metric Control** - Participants ask to have control over the optimization metric and be able to choose the level of automation they prefer.

6.7 Discussion and Design Implications

This test grants insight into participant interaction with the interface, as well as participant understanding and behavior with bandwidth heating.

The first research question, '*How do users interact with bandwidth heating, and what factors influence their ability to set it effectively?*', can be answered that users seek automation, and indicate little desire for manual adjustments. The ability to effectively set the system is influenced by a participant's understanding of the system and the effects of bandwidth heating. Familiarity with technology seemed to indicate whether a participant confidently pressed each button or was hesitant to.

Research question two, '*Do users intuitively understand and apply the concept of bandwidth heating when making heating decisions?*', is where most participants aligned behind using a bandwidth in their heating decisions. Participants grasped that bandwidth could lower their costs and adjusted their heating to include it. Participants weighed their perception of comfort in bandwidth, with cost benefits.

This proves the hypothesis '*Users will correctly adjust their bandwidth based on cost and comfort considerations, while attaining their desired temperature.*'. Participants did not state increasing the temperature beyond their usual desired temperatures. When presented with the scenario of feeling cold, some participants said reaching for a sweater instead of increasing the thermostat temperature, this is an indication these questions were answered from their own heating habits.

Chapter 7: Design Requirements Assessment

Current concept state is tested against the list of requirements, to reveal improvement areas for the final concept iteration. The color of a row corresponds to its fulfillment of the requirement.

Table 9: List of requirements with completion color-coded

#	Requirement	Validation	Development Focus	Assessment Notes
1	The bandwidth mechanism must account for Loppersum circumstances (freestanding homes, local weather) in calculating benefits.	Feasibility Viability	**Coding**: Integration of climate data and house parameters.	*Code accounts for circumstances, and uses data from a nearby weather station*
2	The bandwidth mechanism must use cost-optimization mechanisms.	Feasibility Viability	**Coding**: Implement price-steering mechanism.	*Results indicate cost-savings as the primary effect of bandwidth heating*
3	It must be proven that the designed control mechanism allows to optimize heating based on cost while aiding renewable energy grid-integration.	Feasibility Viability	Coding: Both cost performance and green/grey energy consumption plotted to assess.	*Resulting plot in **Chapter X** reveals energy is drawn in times where the grid is likely greener*
4	Personalized bandwidth settings allow a user to set their desired adaptive comfort profile (temperature threshold, drift rates, eco-modes).	Desirability Viability	**Interface**: Implement method to adjust settings to preference.	*The thermostat allows for temperature and bandwidth settings, drift rates are not yet researched*
5	Thermal adaptation relies on expectation, static temperature feedback must be accompanied by temperature inertia expectations, visually support comfort and trust.	Desirability Viability	**Interface**: Visually include temperature trends / system behavior.	*The avatar is created to align users with temperature expectations*
6	The system must operate autonomously while providing users with an intuitive sense of control through visual feedback.	Feasibility, Desirability	**Coding**: Implement automation logic **Interface**: Display system status	*Bandwidth logic is based on user setup and automates on these values*
7	The system must actively promote and display cost savings transparently to build user trust.	Viability, Desirability	**Interface**: Display consumption/cost metrics	*Interface home screen displays cost-comparison between current setup and a conventional fixed thermostat*
8	The mechanism and interface must be validated for desirability through user testing.	Desirability	**Interface**: Conduct A/B, iterative user testing to refine	*A/B- and iterative user testing performed*

9	A non-intrusive collaboration mechanism must be integrated into the final product, whether through shared efficiency, adherence to a standard, or another approach.	Feasibility, Viability	**Interface**: Include subtle social nudge	*Social nudge in notification screen, subtle. Nudge testing recommended.*
10	The system must provide real-time consumption feedback to enhance user awareness and decision-making.	Feasibility, Viability	**Interface**: Provide instant feedback on user interference	*No instant feedback present in concept*
11	The system must demonstrate an automated cost-optimization strategy that is more economical than a fixed-temperature thermostat.	Feasibility, Viability	**Coding**: Comparing bandwidth to fixed, economical benefit must be clear	*Current thermostat logic produces cost-savings over fixed-temperature in plotted graphs*
12	The interface must visually communicate the selected bandwidth, ensuring users can understand and adjust settings easily.	Desirability	**Interface**: Feedback to communicate selected bandwidth through animation or color-coding	*A dynamic selection bar is designed to communicate bandwidth and allow inputs from users*
13	The interface must include intuitive visual cues to effectively communicate with users.	Desirability	**Interface**: Use icons, animations and feedback loops	*Concept features animations, icon menus and feedback loops akin to familiar interfaces*
14	User interference should be restricted to temporary adjustments, ensuring the system remains autonomous in managing heating efficiency.	Feasibility, Viability	**Interface**: Implement optional time-limited manual override system	*Temporary adjustments not included.*
15	Cost details must be transparent, with a breakdown of expenses and estimated savings displayed clearly.	Viability, Desirability	**Interface**: Clear understandable cost breakdown and savings	*Exact cost structures within HaaS not included.*
16	The benefits of bandwidth heating must be easily understandable for users.	Desirability	**Interface**: Provide explaining element	*Bandwidth heating is explained within submenu*
17	The structure and conditions of Heating-as-a-Service must be clearly communicated and easy to understand.	Viability, Desirability	**Interface**: Introduce tiered plans, comparisons and examples.	*Exact subscription conditions within HaaS not included.*
18	The system must support real-time data processing using energy pricing, weather conditions, and indoor temperature data to optimize heating strategies.	Feasibility, Viability	**Coding**: Integrate real data, digested piece-wise.	*Thermostat logic accounts for these factors, handling all data piecewise*
19	The system must integrate bandwidth heating and collaborative measures while effectively implementing the Heating-as-a-Service model.	Viability	**Interface**: Present collaborative benefits and service model effectively.	*Integration of HaaS Bandwidth and Collaborative measures not included.*

Chapter 8: Final Concept Iteration

The final iteration of the concept refines user interaction and usability based on feedback from the user-testing and the list of requirements. The focus has been on improving **user awareness**, **comprehension**, and **control** over the system while maintaining the efficiency benefits of bandwidth heating. These refinements enhance interface design, with visuals of the improvements on pages 60 and 61.

The improvements are:

- In the **introductory tutorial**, a user is walked through the system, its benefits, expectable behavior, the avatars and the interface. This introduces users to the system and familiarizes them (Page 60).
- The **consumption graphs** are altered to be more easily understandable by turning the bars vertical and adding an explanatory sentence (Page 61).
- Two modes have been added, one to **limit drift rates** and increase comfort at the cost of less economical heating, and one mode to prioritize optimization based on sustainability. Both modes state their trade-off is less economical heating (Page 61).
- Upon adjusting the temperature or bandwidth, the user is presented with an **instant-feedback measure** asking the user to confirm their choice. In this confirmation, a reminder is placed of the consequences of their action and what good practice is to decrease costs (Page 61).

These improvements address all shortcomings identified from user testing with the interface concept. They also improve on the plan of requirements visible in Table 10, previously completed points excluded.

Table 10: Updated requirements based on final concept improvements

#	Requirement	Validation	Development Focus	Assessment Notes
4	Personalized bandwidth settings allow a user to set their desired adaptive comfort profile (temperature threshold, drift rates, eco-modes).	Desirability Viability	**Interface**: Implement method to adjust settings to preference.	*A first venture into drift rate limitation introduced, with implications of drift rate on heating costs.*
9	A non-intrusive collaboration mechanism must be integrated into the final product, whether through shared efficiency, adherence to a standard, or another approach.	Feasibility, Viability	**Interface**: Include subtle social nudge	*Social nudge in notification screen, subtle. Nudge testing recommended.*
10	The system must provide real-time consumption feedback to enhance user awareness and decision-making.	Feasibility, Viability	**Interface**: Provide instant feedback on user interference	*Instant-feedback user interference noting good*

				practice and effect.
14	User interference should be restricted to temporary adjustments, ensuring the system remains autonomous in managing heating efficiency.	Feasibility, Viability	**Interface**: Implement optional time-limited manual override system	*Temporary adjustments included in instant-feedback pop-up; reverts in one day.*
15	Cost details must be transparent, with a breakdown of expenses and estimated savings displayed clearly.	Viability, Desirability	**Interface**: Clear understandable cost breakdown and savings	*Exact cost structures within HaaS not included.*
16	The benefits of bandwidth heating must be easily understandable for users.	Desirability	**Interface**: Provide explaining element	*Bandwidth heating is explained in depth through tutorial.*
17	The structure and conditions of Heating-as-a-Service must be clearly communicated and easy to understand.	Viability, Desirability	**Interface**: Introduce tiered plans, comparisons and examples.	*Exact subscription conditions within HaaS not included.*
19	The system must integrate bandwidth heating and collaborative measures while effectively implementing the Heating-as-a-Service model.	Viability	**Interface**: Present collaborative benefits and service model effectively.	*Integration of HaaS Bandwidth and Collaborative measures not included.*

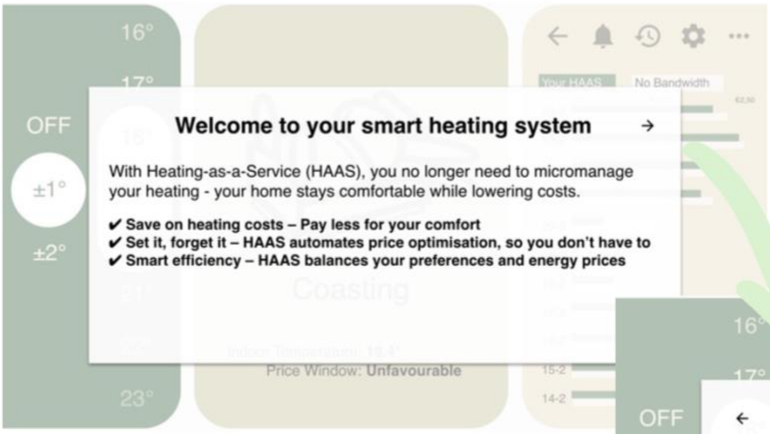
Limitations

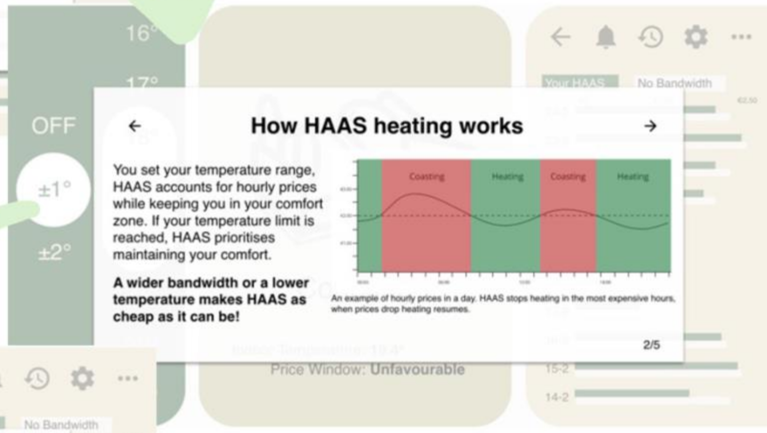
This proof-of-concept focuses on validating bandwidth heating as a model but does not fully explore all aspects of Heating-as-a-Service (HaaS). Specifically, the cost structures (#15), subscription conditions (#17), and integration of collaborative measures (#19) are beyond the scope of this research and require a separate in-depth study.

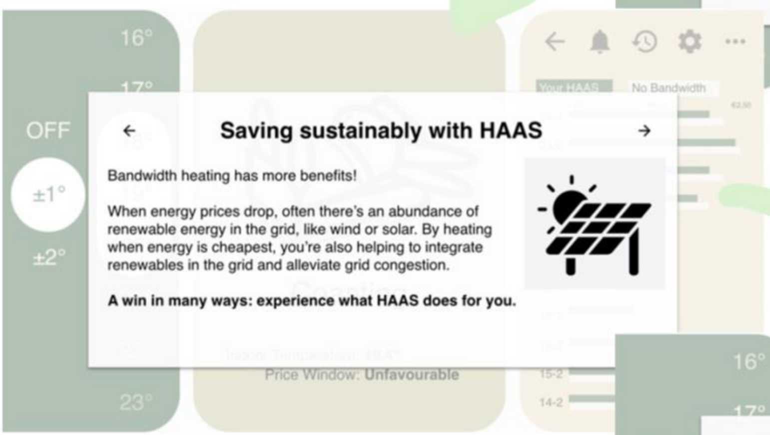
Additionally, while drift rates (#4) were considered as a potential feature, current research does not specifically validate its efficacy in improving heating efficiency. As a comfort setting, adjusting drift rates would allow users to control how gradually temperature changes occur, preventing sudden fluctuations. Future iterations could explore and define this feature as an optional setting.

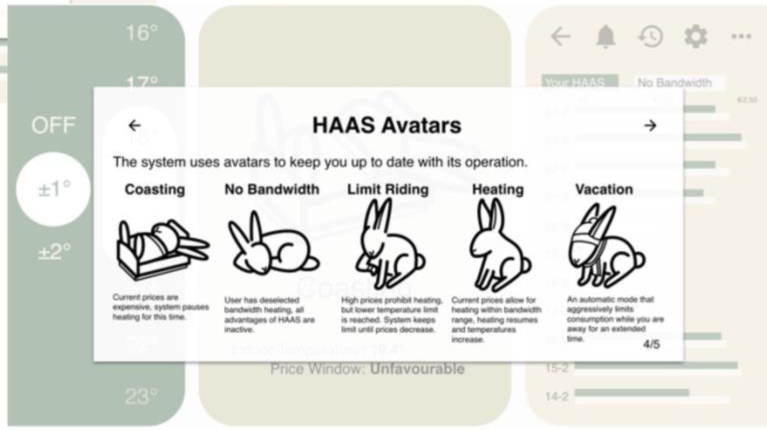
A walk-through of this final concept is visible in video format:
youtu.be/bF_xq8OcZnU

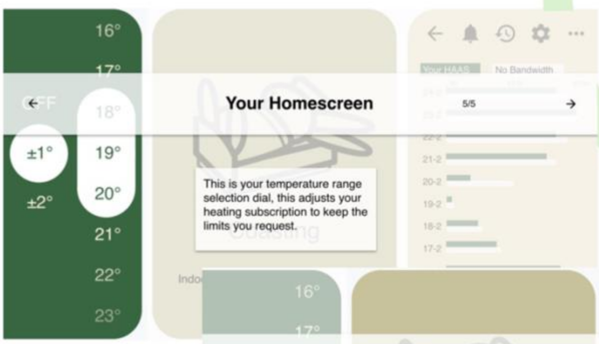
In the introductory tutorial, a user is walked through the system, its benefits, expectable behavior, the avatars and the interface. This introduces users to the system and familiarizes them.



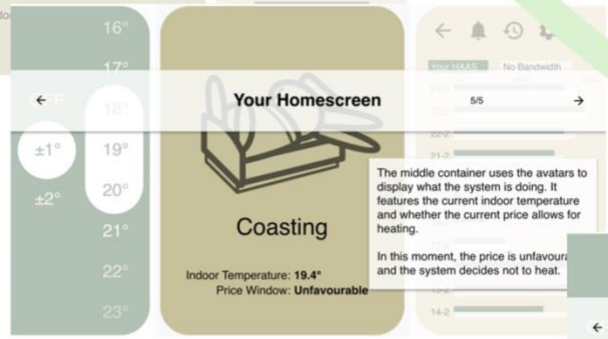


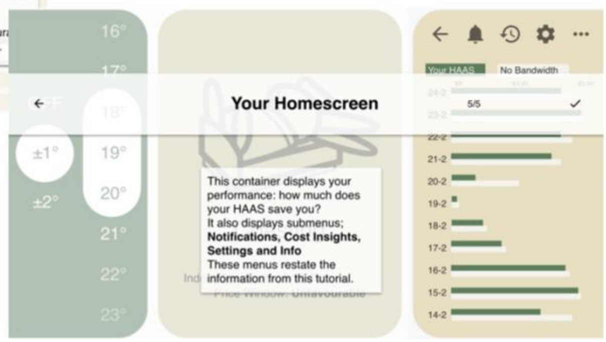


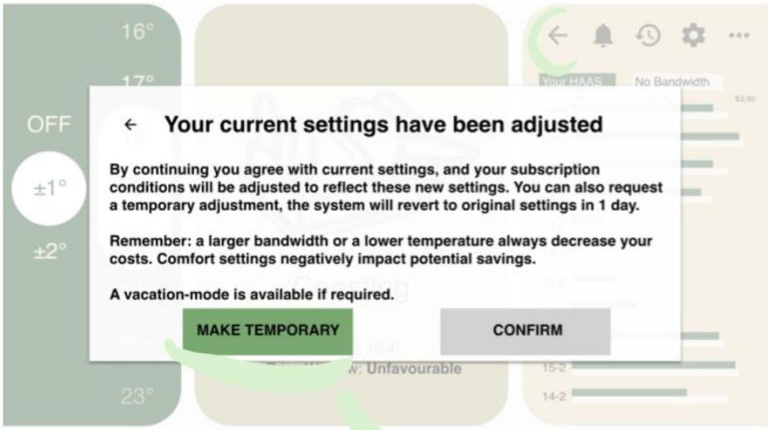




The user is also introduced to the sections of their home screen and what they display.

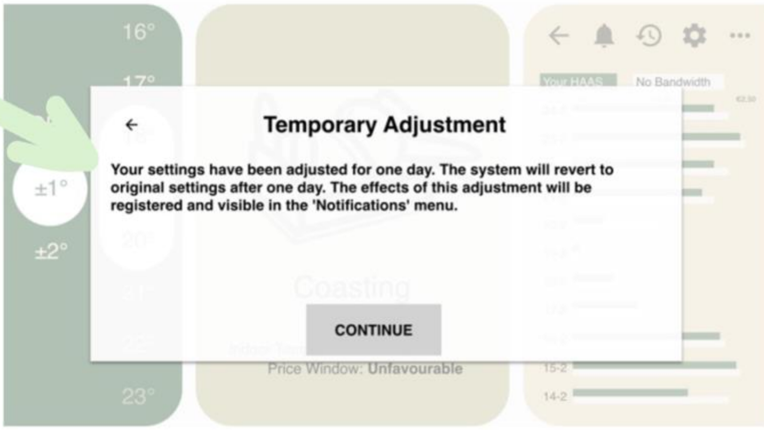


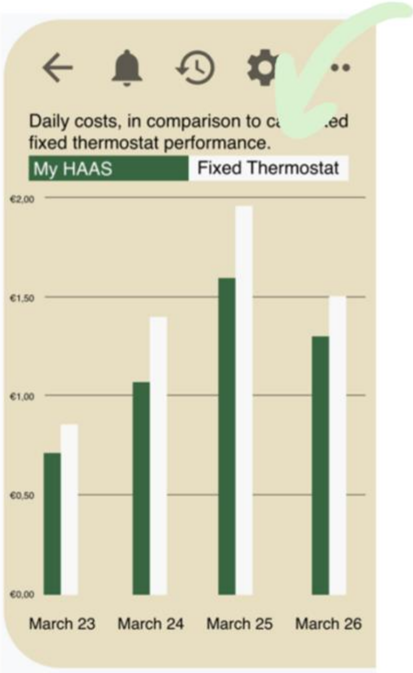




After adjusting the temperature from a previously selected value, the user is prompted with an instant feedback pop-up. Here is made evident the effect of their adjustment and what the most economical settings are. A user can now choose to make their new settings temporary, or accept it as their new permanent subscription.

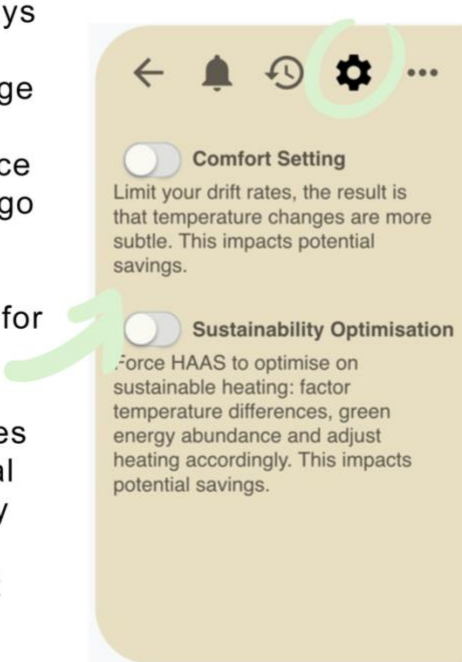
When choosing temporary adjustments, the user is presented with confirmation of their choice and that its impact is registered.





The interface now displays fewer days in a vertical bar graph, making it easier to read. Limiting the time range ensures the data stays within the user's active memory, as performance or temperatures from over a week ago may be harder to recall accurately.

The interface now includes settings for comfort and sustainability optimization. Users can choose to prioritize slower temperature changes (drift rates) at the cost of economical heating. Additionally, a green energy optimization option allows users to select periods when the grid is most sustainable, though this requires additional input data to accurately determine the greenest times.



Chapter 9: Discussion

Recap

This thesis researches HPDH systems, identifies opportunities for cost optimization, and iteratively refines a concept of *HaaS*. The resulting bandwidth heating *HaaS*, is a method to leverage fluctuating energy prices while maintaining comfort. HaaS is developed along two tracks, the heating logic and its user interface, the goal was to optimize heating costs while maintaining user comfort and balancing real-time energy price fluctuations.

Results

Through iterative code refinement, this thesis demonstrates the efficacy of bandwidth heating as a cost-saving mechanism: by leveraging acceptable temperature fluctuations against price variations, HaaS can reduce energy costs by shifting consumption towards cheaper hours. Simulations show an average 12.72% cost reduction based on the past ten years of data. Additionally, the cheapest energy hours often align with peak renewable supply, resulting in the additional benefit of greater sustainability of this bandwidth system. This bandwidth system shifts 95% of its consumption to low-cost, high-renewable energy hours, compared to 51% for a conventional thermostat. To support this shift, the interface educates users on bandwidth heating and guides them in adapting their usage accordingly.

The interface educates users on bandwidth heating and guides them in its operation. Beyond demonstrating cost savings, the results underscore the importance of user engagement in effectively implementing bandwidth heating. The interface is created to test user interaction with bandwidth heating, as well as execute concept testing. Testing indicates firmly that users include bandwidth in their heating behavior, agree with the concept of heat delivery through bandwidth and value the automatic cost optimization. The joint development of an accompanying interface bridges the gap between consumer and the intricacies of HaaS. While the interface effectively addresses user experience concerns, further refinement is needed for the integration of collaborative features beyond that of subtle social nudges and explore the full potential of HaaS. This thesis confirms users are receptive to innovative heating solutions, provided they are educated about it and have a sense of control over the boundaries within which the system operates.

Requirements

The concept is validated through the list of requirements. All requirements but 15, 16 and 19 are met. These pertain to deeper research into cost structures, subscription conditions and integration of collaborative measures. Integration of these requirements into the concept requires separate research in further development of the project.

Desirability

The desirability of the bandwidth heating system is strongly influenced by its ability to balance cost savings with user comfort. User testing confirmed that participants were receptive to financial and environmental benefits. The interface played a crucial role in shaping perception, as clarity in feedback and control mechanisms enhanced trust in the system. Users valued having agency over their heating, without excessive complexity. However, while the system successfully nudges users toward efficient heating behavior, further refinement could strengthen collaborative engagement beyond individual optimization. Overall, bandwidth heating can be an appealing solution, provided it transparently communicates its logic, maintains ease of use, and offers a clear, tangible benefit to the end user.

Feasibility

The technical feasibility of the heating logic depends on the ability to dynamically adjust heat consumption in response to fluctuating energy prices. Simulations confirm that this approach can significantly reduce costs and improve alignment with renewable energy availability. However, implementation presents challenges. HPDH systems are classified as *grootverbruikers*, their ability to modulate consumption dynamically is not guaranteed, as consumption forecasts must often be set before day-ahead prices are released. Additionally, the system's effectiveness relies on real-time data integration, requiring further research into its practical implementation. Another key consideration is the integration of the interface into a hosting device, determining whether it supports the level of control and automation required for HaaS. While technically feasible within this concept, successful deployment hinges on overcoming these constraints.

Viability

The business viability depends enhancing the competitiveness of district heating while aligning with the pricing strategies of semi-government entities like Alliander. HaaS offers a value proposition by reducing heating costs for consumers, improving the attractiveness of HPDH as a heating solution, strengthening its position against gas boilers. However, as a semi-government agency Alliander cannot prioritize profit maximization but focusses on providing heat at the lowest possible cost while aligning with their innovation and sustainability goals. This variation of viability aligns with the outcome of this project.

The profitability of HaaS is tied to how dynamic pricing structures in the subscription evolve. If pricing schedules reflect real-time energy market fluctuations with an overhead to maintain the system, economic benefits to users are guaranteed while sustaining itself as a viable service.

A viable business model could emerge through a subscription-based structure, offering different levels of heating flexibility. Ultimately, while bandwidth heating strengthens the economic case for HPDH heating, its long-term viability depends on cost management.

Conclusion

In conclusion, this research contributes to the ongoing development of HPDH as a sustainable and competitive alternative to traditional heating systems by innovating on the user's edge of this technology. By optimizing user interaction through an intuitive interface and dynamic heating approach, this research not only enhances HPDH efficiency but also sets a precedent for future developments in energy-efficient home heating. The findings affirm the viability of bandwidth heating as a scalable and impactful innovation in sustainable heating solutions.

Limitations

While the results demonstrate the feasibility and economic benefits of bandwidth heating in HPDH, several limitations and areas for further research remain. A key constraint is the regulatory framework governing *grootverbruikers*, which currently requires them to submit a consumption prognosis in advance. This means that, while dynamic steering of heat consumption is viable at the individual household level, it is constrained for the MES. Without the ability to dynamically adjust demand in response to real-time energy prices, the full potential of bandwidth heating remains partially unrealized.

Beyond optimizing costs for end users, there is an additional layer of opportunity in refining the operation of the MES. Currently, the optimizations in this research focus on consumption behavior, but future work could investigate how MES itself could adjust its heat production, storage or distribution strategies to better support bandwidth heating.

Additionally, the cost and subscription structures in HaaS require development. While this research outlines pricing strategies, the structure of district heating subscriptions and how they interact with flexible pricing requires further development. This mechanism is crucial for defining and ensuring the long-term viability of HaaS.

Another notable limitation is direct collaborative features in the interface design. The system incorporates subtle social cues, but it does not facilitate explicit cooperation or shared decision-making between users. Further research could test ways to enhance collective engagement, potentially leveraging community-based incentives or shared energy goals within a more developed concept.

On a technical level the current heating logic requires refinement, particularly in terms of limit-riding behavior and adaptive response to external factors. While this iteration identifies significant economic advantages, real-world implementation may introduce complexities that are not fully captured in the simulation. Future work should include empirical testing in live HPDH environments to validate cost savings and user experience under real operating conditions. Despite these limitations, the findings confirm that bandwidth heating holds strong potential as a cost-saving and sustainability-enhancing innovation, provided that regulatory, technical, and user engagement challenges are adequately addressed.

Recommendation

This thesis proposes a staged approach to further development, each stage including developments to iteratively test:

1. Concept Refinement – Further address constraints for *grootverbruikers*, explore MES-level optimizations in heating and consumption and review cost and subscription structures.
2. Heating Logic – Develop the heating logic and prevent limit-riding, adaptive responses and real-world feasibility through expanded simulations.
3. Integrate Data Streams – Integrate and test the improved HaaS against live data streams of energy prices and weather conditions.
4. Hosting – Progress on a suitable hosting device or method of communication between user and system, supporting the developed concept and steering-requirements for HaaS.

These steps will evolve the current concept into a validated scalable product proposal, fit for real-world testing and grants insights into viability and long-term sustainability of this heating within this structure.

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Appendix

Appendix A: Heating Behavior Survey Results

Figure 29 shows the distribution of respondents across homeowners and those that rent or stay. The main conclusion from this question is that 70% of respondents, in some way, can make decisions that pertain to their energy contract. This shows that a significant percentage of respondents have access to decision making over their heating system.

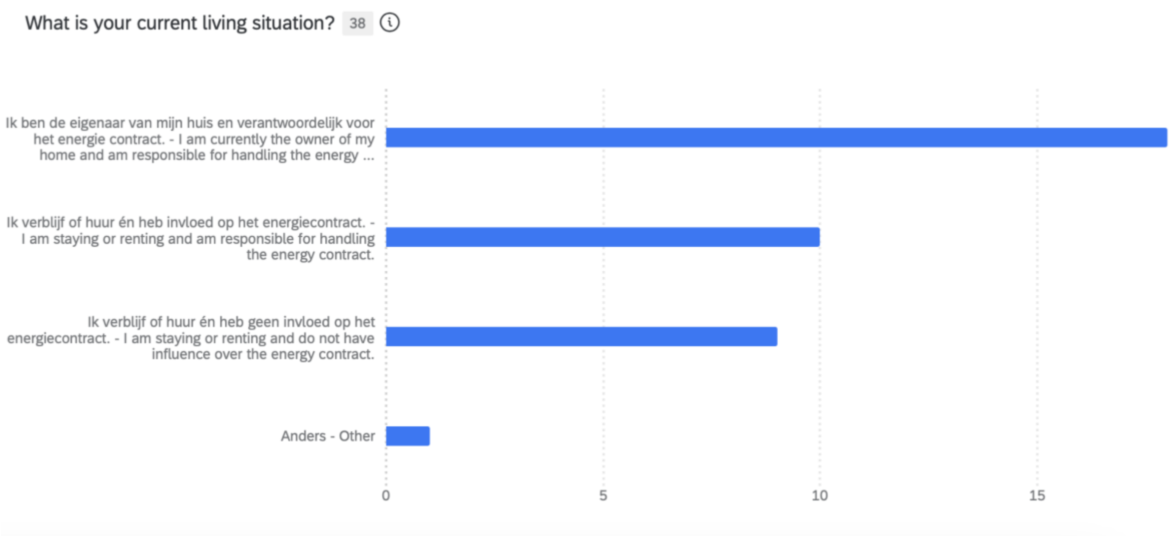


Figure 29

Figure 30 shows the relative self-assessed state of maintenance of the homes of respondents. From this result we can conclude that 90% of respondents live in a decently to well-maintained home. This bodes well for the efficacy of heat pumps, that require limited heat-loss.

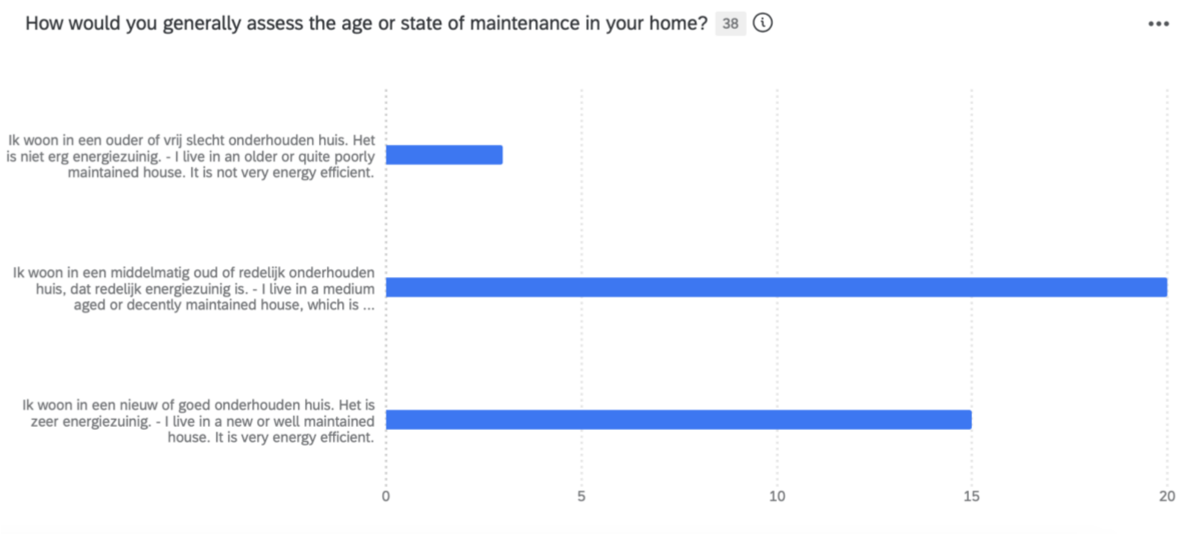


Figure 30

Figure 31 shows current heat sources in the homes of respondents, with a majority 65% of respondents currently drawing heat from a gas kettle. This shows how a large number of respondents are subject to gas prices, for which HPDH can be designed as an economical substitute. This is also the most promising sector for which HPDH makes sense in terms of reaching a carbon-neutral future. Other methods of heating require a different approach when implementing HPDH, for example replacing electric heating with a closed radiator system.

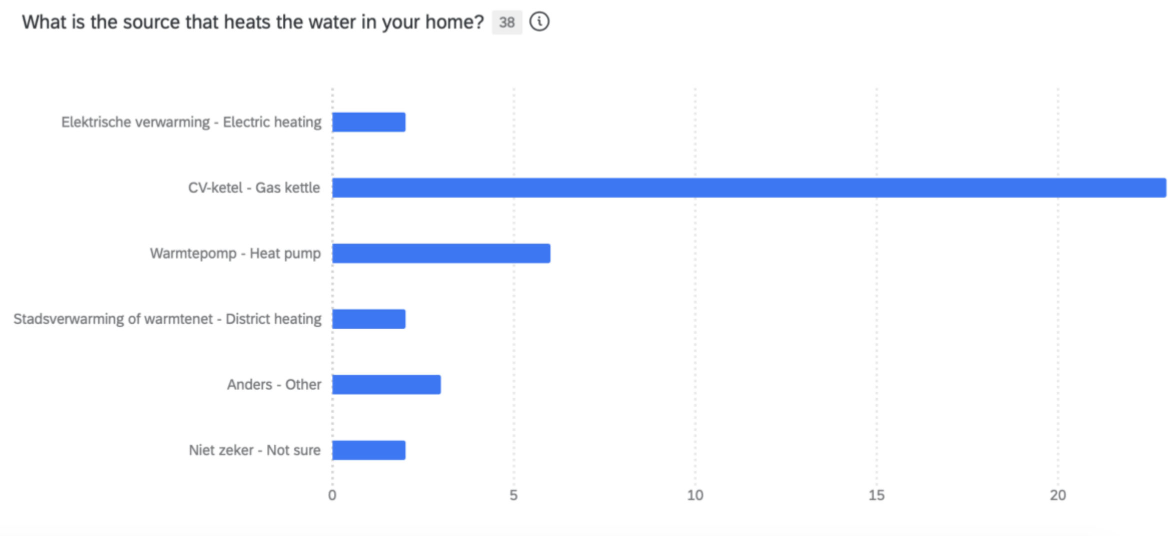


Figure 31

Figure 32 shows the distribution of respondents among their tendency to adjust and interfere with their heating. 50% of respondents adjust their heating one or more times each day, at the other end 30% of respondents adjust their heating on rare occasions. From this it can be concluded that 50% of people value control over their heating system, and that they fall within the category of people whose behaviour is undesirable in the HPDH system because alterations cause imbalance and less efficient behavior. We can also conclude that another 30% of respondents exhibit the wanted behaviour, though this can be attributed to the fact that they may have a programmable thermostat, or an extremely well insulated house.

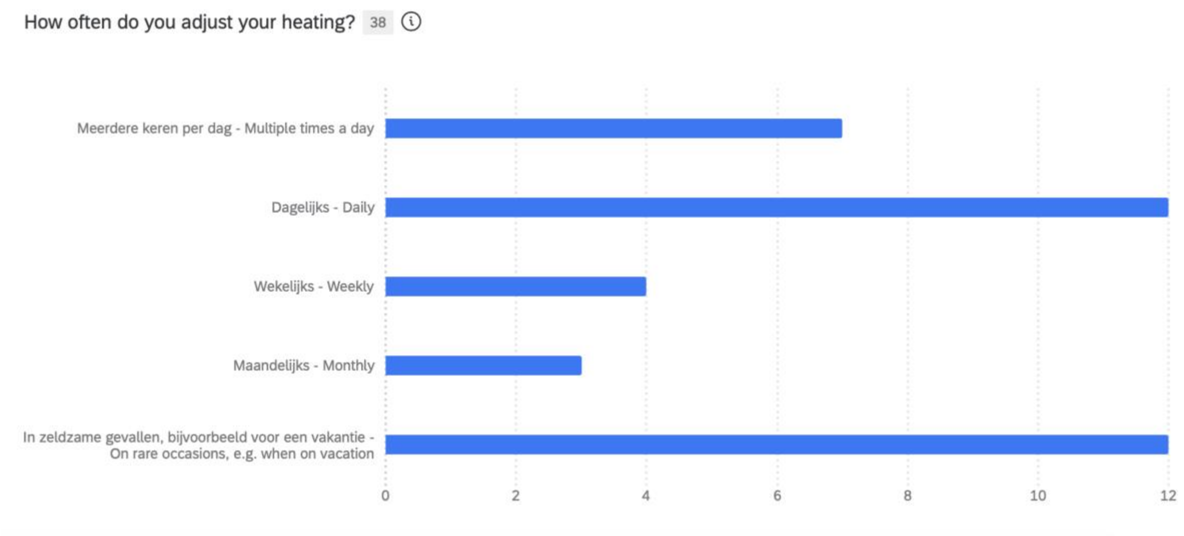


Figure 32

Figure 33 shows how 40% of respondents says to be actively looking for ways to decrease their heating consumption, another 45% says to be open to it if an accessible solution would be offered to them. These results show how there is a strong demand to decrease costs, and that it is an active priority for many respondents.

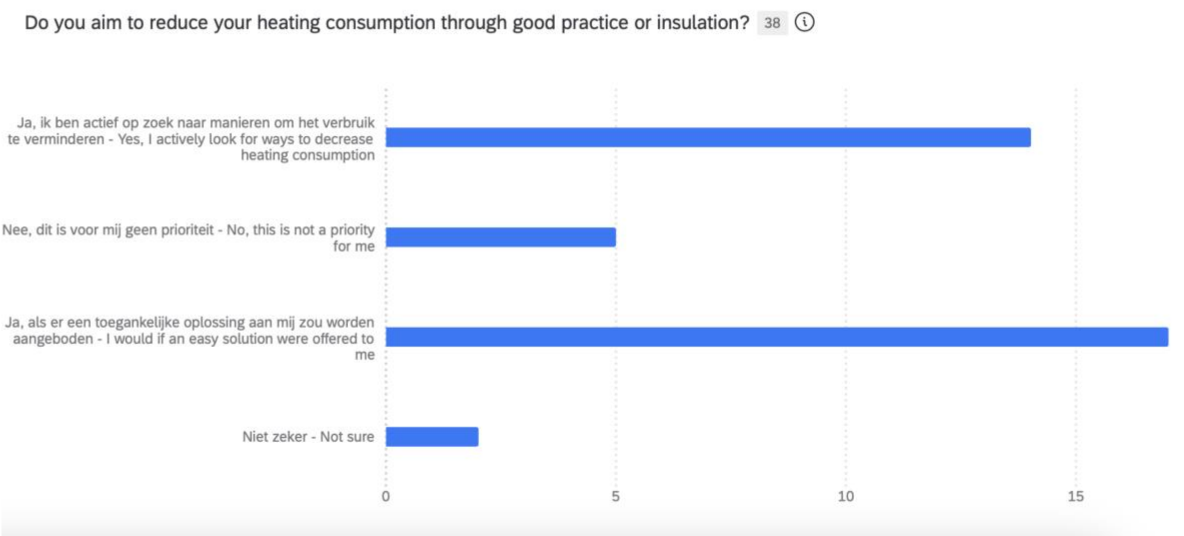


Figure 33

Figure 34 shows a question which was aimed to assess whether respondents were open to outside intervention in their heating to assure lower costs, through heating system activation during 'cheaper' times. The way in which the question is phrased however, is as simple as 'Do you want the same, but for less money?'. This means that the question does not serve its purpose but only shows that reduced costs are always welcomed.

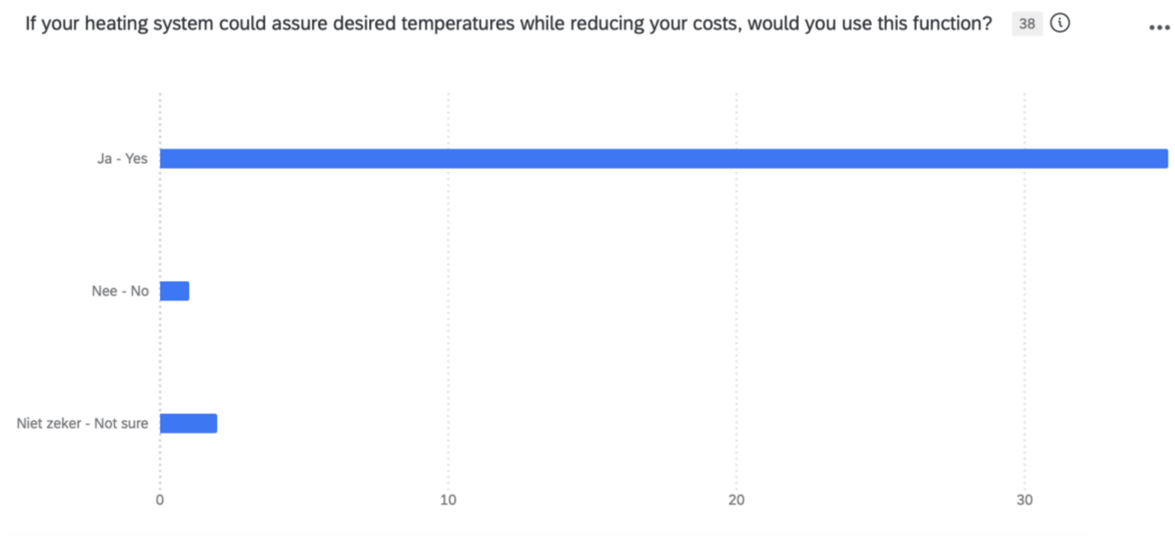


Figure 34

It was inquired in an open question whether users could reproduce a specific instance when their heating system disappointed them, the users were free to type their own response. Responses that were Dutch have been included with a translation. Answering was not mandatory. Answers below.

- De verwarming heeft geen thermostaat waardoor nauwkeurig (of energiebesparend) verwarmen niet mogelijk is – **The heating system has no thermostat, so accurate (or energy-saving) heating is not possible**
- Het warm water uit de boiler is soms op – **Hot water from the boiler runs out sometimes**
- Kapotte ketel – **Broken boiler**
- de batterijen van de thermostaat waren op en toen stuurde die de verwarming gewoon niet meer aan, waardoor het huis ineens 4 graden was in de winter nadat iedereen een weekend weg was geweest – **the thermostat batteries ran out and then it just didn't control the heating anymore, so the house was 4 degrees colder suddenly in the winter after everyone had gone away for a long weekend**
- Oude systeem was blokverwarming, ik betaalde vooral voor de niet zuinige buren - **Previous system was district heating, I paid for the non-frugal neighbors**
- A toon (smart home thing) that did not seem to work, besides indicating the temperature.
- Een slimme thermostaat die niet werkt (toon) – **A smart thermostat that didn't work (Toon)**

- Enigszins indirect. Ik woon in een oud en slecht geïsoleerd huis en de temperatuur waarvan het smart systeem aangaf dat het energiebesparend was (dus niet te hoog), kon ons huis niet genoeg verwarmen. Dat was frustrerend, omdat we er wel bewust mee bezig waren. – **Somewhat indirectly. I live in an old and poorly insulated home, and the temperature that the smart system indicated as energy-saving (so not too high) could not heat our home enough. This was frustrating because we tried to be conscious of it.**
- Ingestelde temperatuur werd niet gehaald… - **Set temperature was not reached…**
- Vloerverwarming kost enorm veel energie om de woning (60m2) op te warmen. Omdat het nieuwbouw is en goed geisoleerd is, zet ik de warmte eigenlijk te laag (16c°),maar blijft de warmte goed binnen – **Underfloor heating takes a huge amount of energy to heat up the home (60 square meters). Because it is a newly constructed home and well insulated, I actually set the heat too low, though the heat is kept in well**
- Storing in ketelhuis – **Malfunction in boiler room**
- Ons appartement is standaard té warm, ook als de verwarming uit staat. - **Our apartment is too hot by default, even when the heating is off.**
- Not warm enough in winter, maybe the room's lack of ability of keeping temperature

A few remarks here show promise for an HPDH system. For example the ability of the gas kettle to be empty, which is something an HPDH system can be optimised for to never occur. Also a remark on paying for neighbours in a district heating system; this hints towards the 'collaborative' contribution in the project. A few remarks included the Toon, that has ceased its intended functionality. One remark speaks of disappointment when desired temperatures were not met. A correctly tailored system could alleviate this issue.

These remarks are things to keep in mind in development of a product for HPDH and ensure a promising value proposal.

Figure 34 is an answer distribution that shows 30% of respondents are either not able, or not willing to switch to a different heating system. Of the respondents that are open to switch, economical and sustainable heating are the main desires.

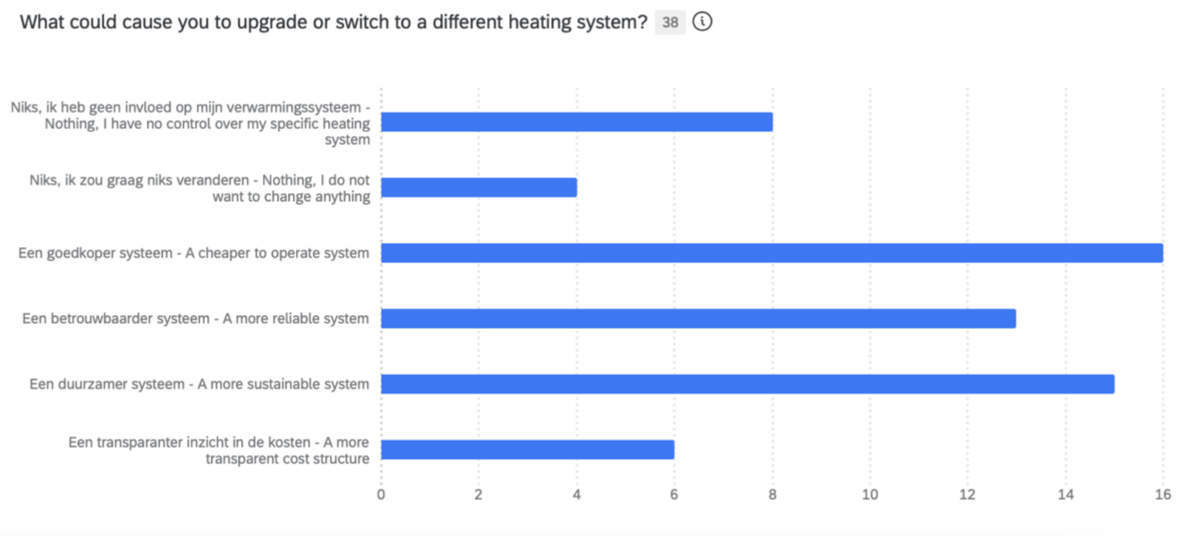


Figure 34

Generally, the survey shows that respondents generally want to drive down costs, live in homes that are appropriate for HPDH, are open to different heating systems, if they are sufficiently sustainable or economical. View other takeaways in main report body.

Appendix B: Design in One Day

The execution of this method walks the path of developing in a product-centric approach where interface and physical appearance are prioritised. In development, this approach is given partial priority as the efficacy of a bandwidth system is to be proven as well. In development and testing of an interface to accompany the bandwidth thermostat the *design in one day* (DIOD) granted crucial insights. Success looks like a user-friendly, integrated heating system where users feel in control of their heating, but the system smartly manages consumption. Limitations in this method are taking no longer than 8 hours and using digital tools. Using *How to* questions, the intermittent conclusions from the survey and literature review can be used to remain at the core of the issue. As visible in Figure 35, the questions used to ideate are:

- How to address peak demand?
- How to introduce collaboration into a system?
- How to encourage behavior change?
- How to create a product for seamless interaction between user and system?

These four revolve around prevalent issues to be dealt with in interface design, while staying concise enough to be dealt with in a rapid fashion as DIOD requires. Brainstorming on these questions resulted in possible design solutions.


HaaS: heating against subscription type offers, less interference as it is taken care of
Bandwidth around desired temperatures to soften peak
°C
Pre=Heat during offpeak
Offer morning/evening consumption subscriptions with accompanying costs differences
Apply '4/5 users already...' to create community responsibility
Gamification!
+128 points!
Inform and educate users on effects and costs of behavior
STOP
H2
address peak demand
Automation over user interference
Divide network into morning and evening demand
'Billboarding' performance
MES
€€€ Comfort
€ Eco
Heating modes communication based on cost
Staggered heating order to lessen sudden peak
Zone heating during peak hours
Time-of-use pricing
User alerts for demand periods, to be increase consciousness
Accept all
Have automisation and eco behavior be the standard
Insight into collective impact
Shared goals
Incentivise good practice
DAYS SINCE ACCIDENT
Dynamic pricing that aligns with system desire
Real-time feedback
H2
Introduce collaboration into a system
Community platform
Community events
AUG 9
HEAT EVENT
Local energy trading
Consumption partnerships
Gamification elements to entice
Create trust in automation
Personalised Efficiency Goals
Real-time feedback
Performance comparisons to community
H2
encourage behavior change
Tier pricing to punish undesired behavior
Introduce personal challenges
Long-term incentive programs
User education
Assist in automation
Gamification
Display that can be instantly read to assess system status; peak saving, demand management, eco-mode or pre-heating
Operator letters of updates
An app with an intuitive user interface to monitor and educate
Collaborative decision making on community preferences
Personalised user profiles
H2
create a product for seamless interaction between user and system
Gamification to entice more interaction with the system
Voice control and audio feedback
Provide suggestions and propose best practice for user comfort and cost
Predictive heating to ensure optimal comfort
Thermostat as main point of interaction
Efficiency-driven overrides to dissuade undesirable user behavior
Real-time feedback on current settings or interference from users
JUNE
Energy budgets per month, week to help users stay within their limits
Context aware notifications; sense temperatures, energy draw, desired averages

Figure 35

Consequently, through selection of promising results the basic functionality of a required prototype is defined (Figure 36).

Figure 36

The selected design aspects are:

- **Bandwidth heating**, this proposes a system that manages the heating system to float around a set desired temperature. This mechanism can be used to flatten demand peaks or optimize for cost-effective heating by coasting during expensive hours.
- **Pre-heat**, is a function of bandwidth heating as to allow excessive heating over desired temperature playing into aforementioned benefits.

- **User alerts**, which warn users of price peaks, demand peaks or prevent their interference.
- **Heating-as-a-Service** (HaaS), this emphasizes ownership and influence remains with Alliander for optimization and system management. Users buy into the service of space heating, as opposed to buying a heating system outright. Additionally, this allows Alliander to offer 'subscription-style' heating which meshes well with possible bandwidth offerings.
- **Shared goals**, where 'collaborative heating' can take shape. A neighborhood could monitor their performance and receive personalized goals or metrics to nudge towards efficient heating.
- **Real-time feedback**, where a user is instantly notified of undesirable behavior such as increasing the desired temperature.
- **Consumption partnerships**, where users can decide to accept a partnership to engage in competition over lower consumption, or perhaps divide their hot water use complimentarily.
- **Tier pricing**, where temporary heating beyond a set subscription or bandwidth is penalized excessively to dissuade excessive heating.
- **System display**, where the status can be read easily from a distance. This can create trust in the system as users see the status change over time. It can also create understanding in users when they realize that heating is being optimized for them and does not require intervention.
- **Provide suggestions**, so users can be subtly informed on best practice.
- **Energy budgets**, keep cost structure transparent as to generate trust when users see exactly how the system has operated and which costs it has been able to minimize.

This ideation is the foundation on which the concept relies (Figure 36). The interface here is kept simple to not deter users with excessive stimuli and prevent misunderstanding the way it operates. It is drawn in a way that could indicate either a wall-mounted or freestanding product, user preference between these options is investigated in the A/B-test.

Figure 36

The main features consist of selected design aspects. Described from left to right. The 4 colored LEDs represent system status and communicate to the user that the system is operational and adjusting its behavior based on circumstances. The ‘cost’ indicates current behavior of users, actions such as increasing temperature demand in a demand peak will display as worse behavior. The information point indicates a subtle nudge for the user to decrease their consumption. Next to that is the consumption partnership, where a neighboring home’s consumption ‘score’ could be displayed to instill some competition as a communal goal. Lastly the interface displays the set desired temperature, as well as the current deviation from it (within bandwidth). The scroll wheel allows for instant temporary adjustment when demanded by the user. When done so, an instant-feedback system alerts the user on what their decision could mean for their consumption and costs.

In addition to the interface, non-visible features include bandwidth heating with subscriptions based on temperature range allowances. A subscription with a bandwidth of 1 degree could be more expensive than a 2-degree subscription. Energy budgets and cost transparency are left out of this product and can be reached through a separate online portal. This is done to not clutter the interface unnecessarily. The subscription system is offered to users through Heating-as-a-Service, of which exact parameters, terms and conditions require further definition.

Outcome

The DIOD method provided insight into developing a product for smart management of heating systems and the user-interface relationship. This specific approach highlighted a product-centric perspective where key challenges and opportunities emerged.

Key challenges emerged in balancing user control with system autonomy, for which cost transparency could be an aid. The issue lies in the desire of users to control the system, though the bandwidth is designed to work best when not interfered with. Clear cost transparency could convince users of efficacy. Another challenge is developing Heating-as-a-Service to be intuitive and appealing; it is a concept users are not familiar with.

The ideation, guided by How-To questions, established that aspects such as bandwidth heating, Heating-as-a-Service and a clear system display are key aspects in the success of the product. Bandwidth heating could grant optimization of heat consumption, where the Heating-as-a-Service could incentivize users to not interfere and understand the new interaction with heating through this system. Lastly the interface is where this all comes together and the portal between user and system.

This exact concept is not representative, but does grant specific insight into the design project. Clear communication of system behavior, balancing users and automation.

New Requirements

- The interface must use clear visual indicators to display system status intuitively.
- User control is limited, allowing system autonomy to balance consumption effectively.
- Users must have easy access to a transparent breakdown of heating costs and system performance via a dedicated method.
- Users adjustments are met with real-time feedback to inform them of their impact.
- Bandwidth heating implementation and its benefits must be clearly understandable to users.
- Users must clearly understand the conditions of Heating-as-a-Service rather than direct manual control, as well as its benefits, limits and operational terms.

Appendix C: User Scenarios in System Architecture

When the subscription is adjusted	When summer arrives	When energy prices peaks	When user interferes	When energy prices drop
User requests subscription adjustment	Register outside temperature	Hourly price rises above threshold	Control algorithm override	Energy price forecast: cheap
Reset base target temperature	If outside temperature is above 19, cease heating	If current temp above minimal bandwidth: cease heating	Output heating system to heat to 'new' temp	Check current temp in home
Bandwidth adjusts around new target	If required heating is negative (cooling), cease heating	Coast for duration of peak or;	User interface notifies of intervention	If current temp is under upper limit
Control algo adjusts heating system	Monitor outside temperature	Coast until lower bandwidth limit	Consumption meter registers interference	Set system to start heating
User interface displays new state	Engage bandwidth if temperatures decrease	Maintain temp if lower bandwidth reached	Heating starts, beyond subscription	Register consumption
Costs of adjustment notified	Notify user on proceeding	Increase temp if price allows	Additional costs, beyond subscription	Determine costs based on subscription T&C's
Costs tiered from new base state	Benefits of intervention logged	Notify user on proceeding	Bandwidth is adjusted to new set	Notify user on proceeding
Control algo operates at new base state	Continue operations as bandwidth	Determine costs based on subscription T&C's	Reset to subscription temp at night	Register savings, present to user
			Costs of intervention clearly logged	
			User receives reports	

Figure 37

Appendix D. Code Testing and Validation

Figure 38 shows how moments of significant heating output are directly followed by an increase in indoor temperature.

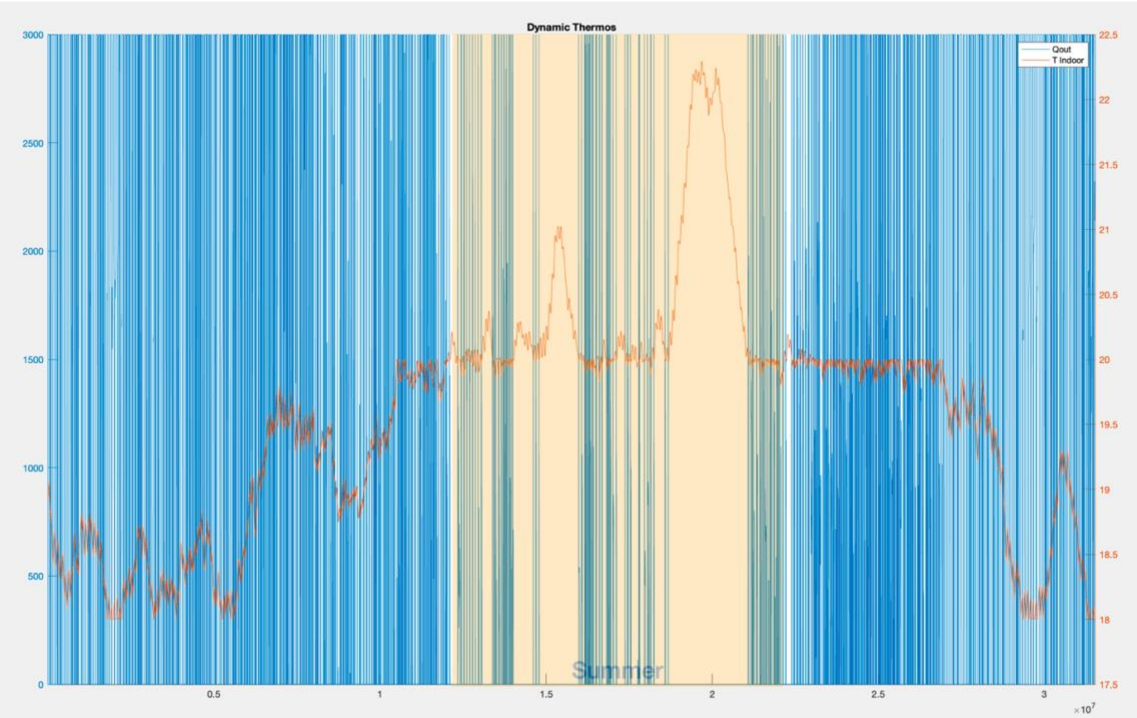


Figure 38

Figure 39 shows how the mean daily price (€) is accurately calculated and multiplied across each day of the year.

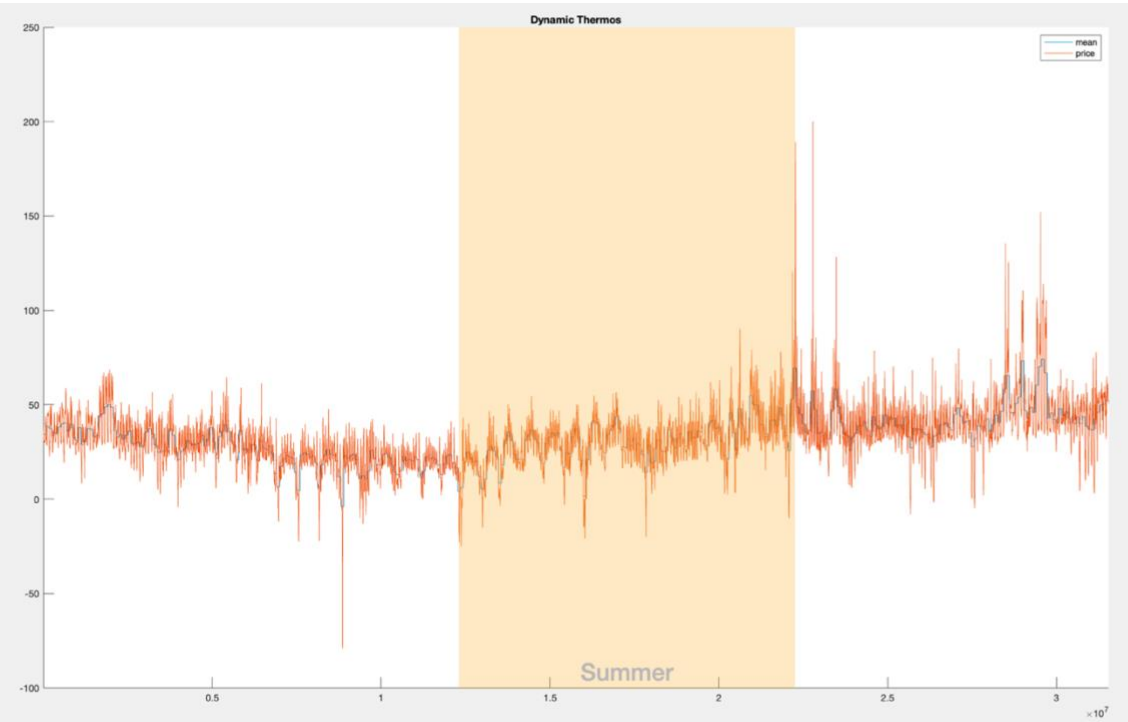


Figure 39

Figure 40 indicates the behavior of the fixed thermostat and the effect of its behavior on the indoor temperature. It succeeds in maintaining 19°C within its 3000W output limit.

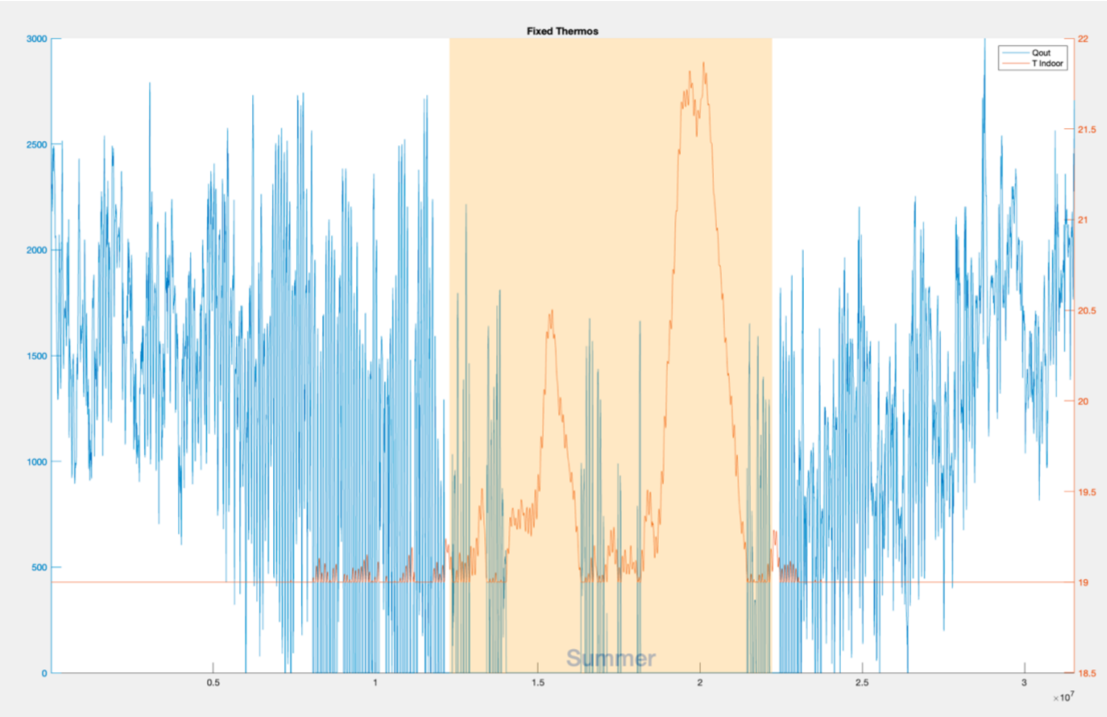
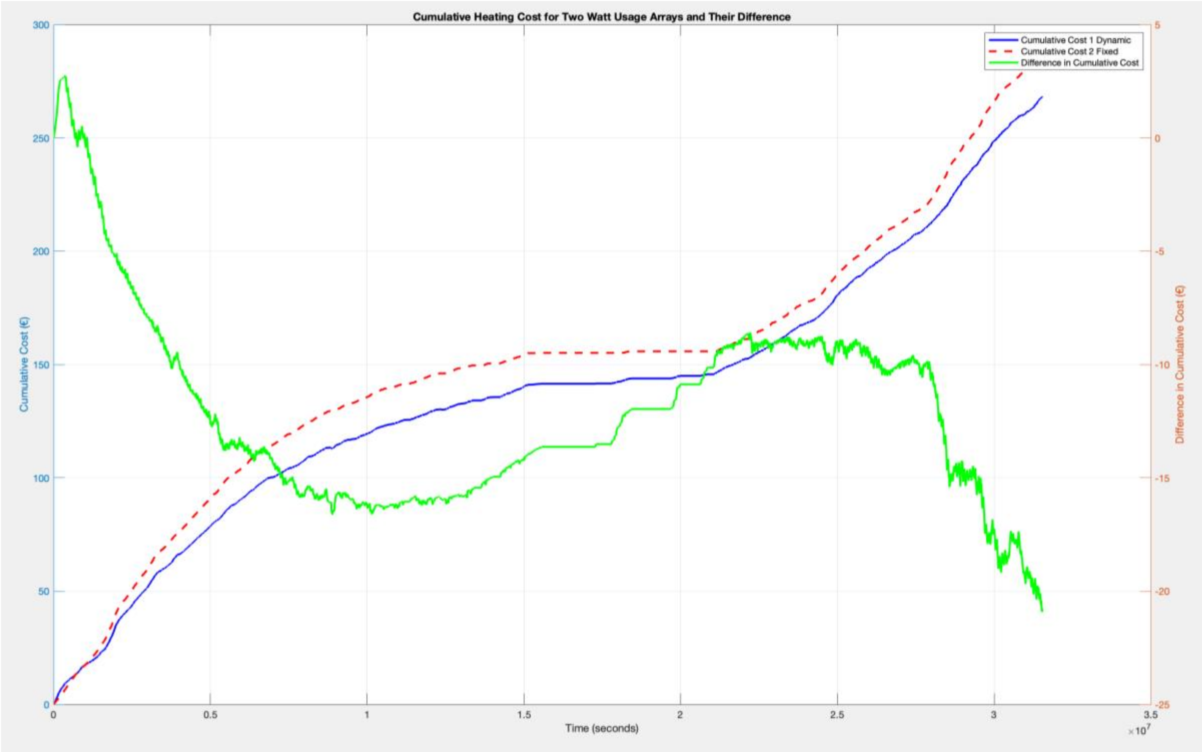
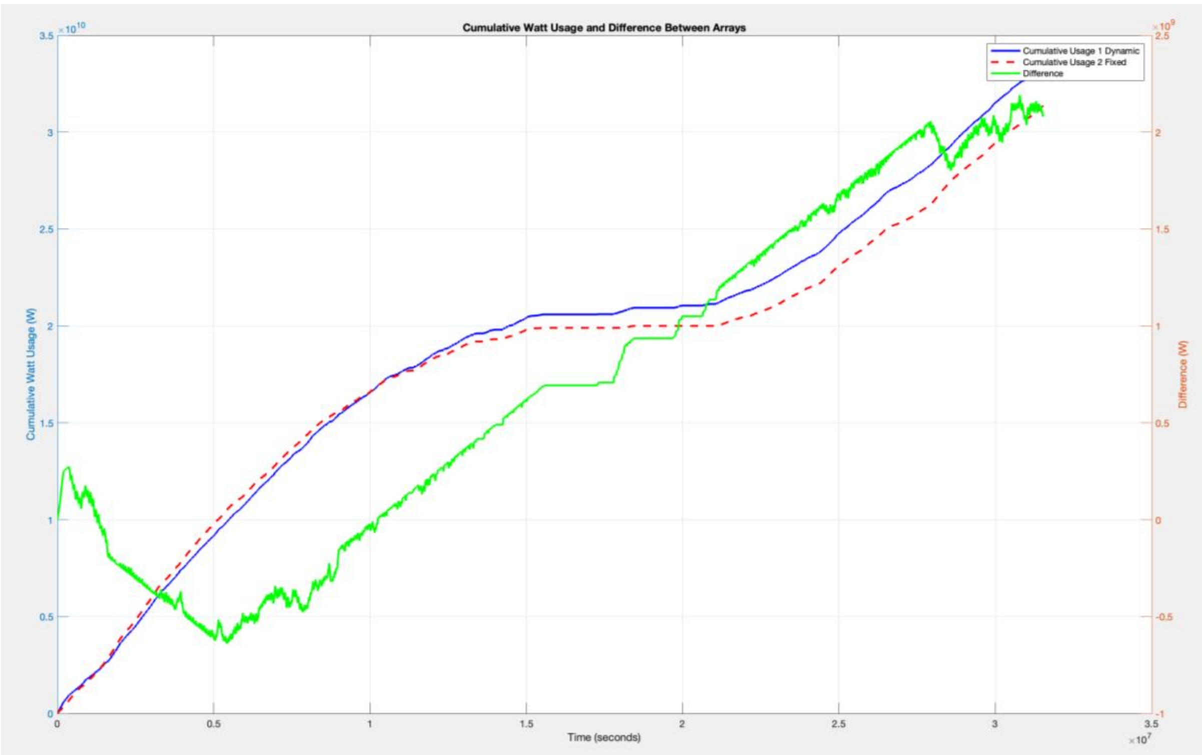


Figure 40

Appendix E. Result Graphs

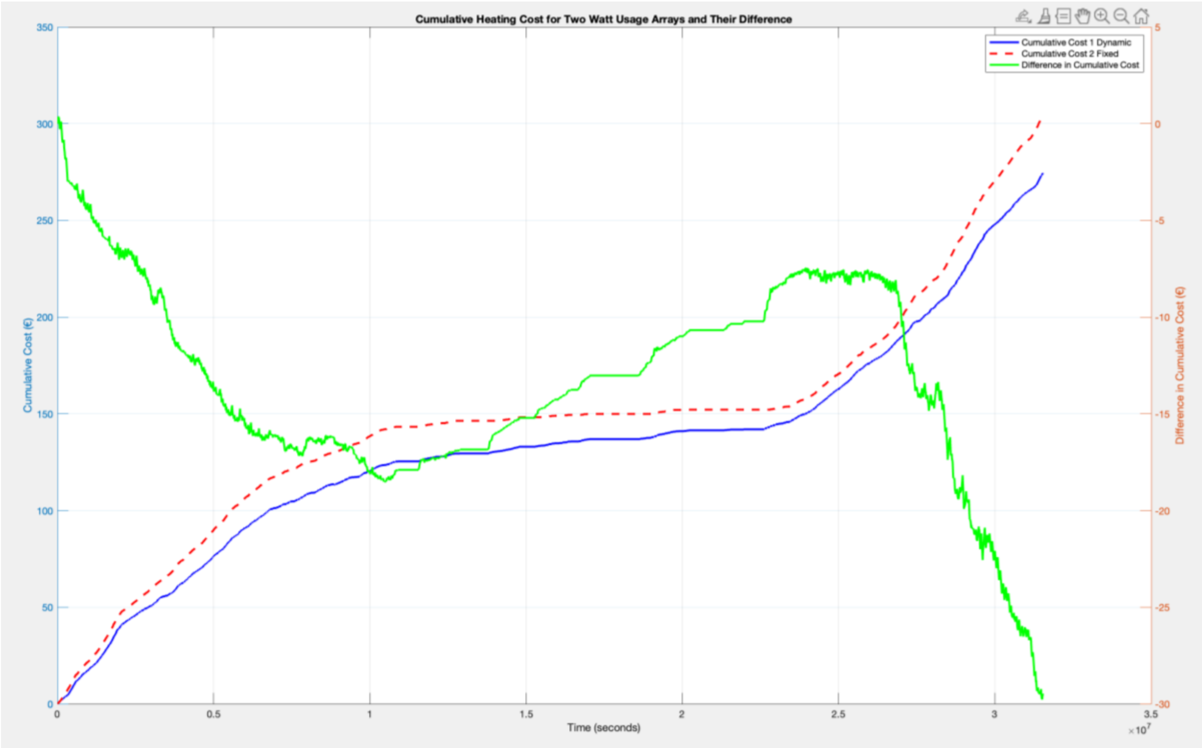
2015: Costs: -7,19%, Output: +6,56%

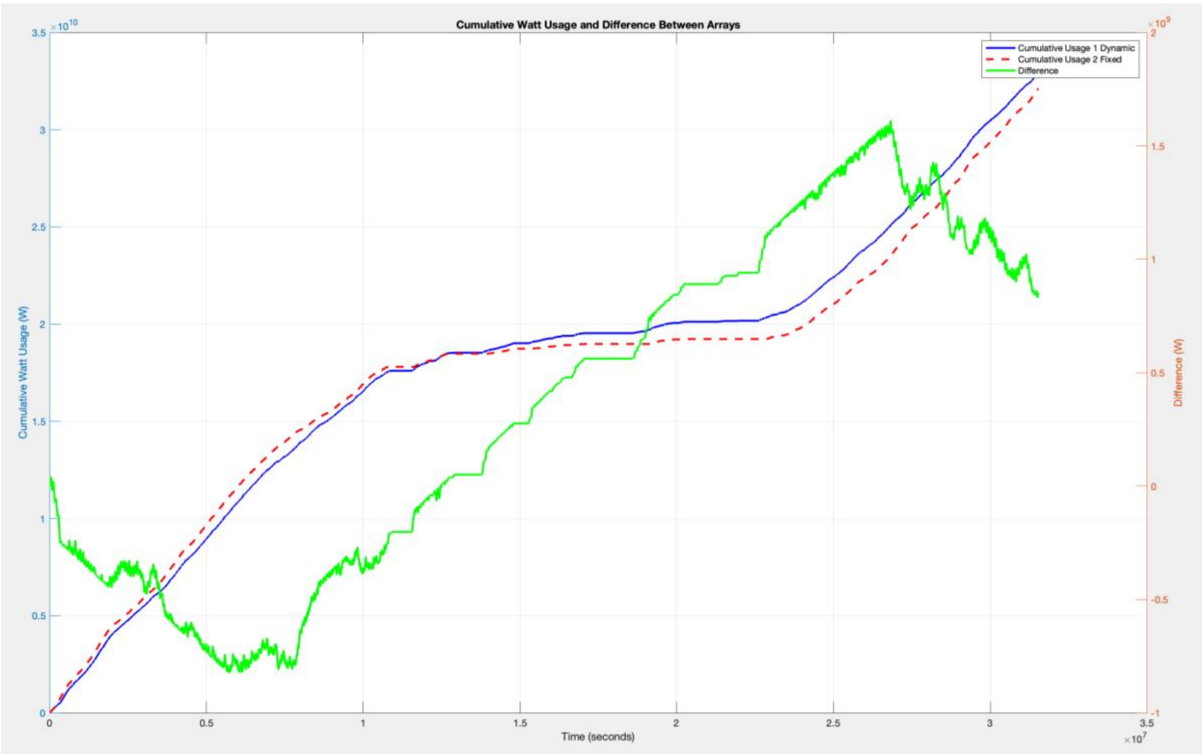




Figures 41 & 42

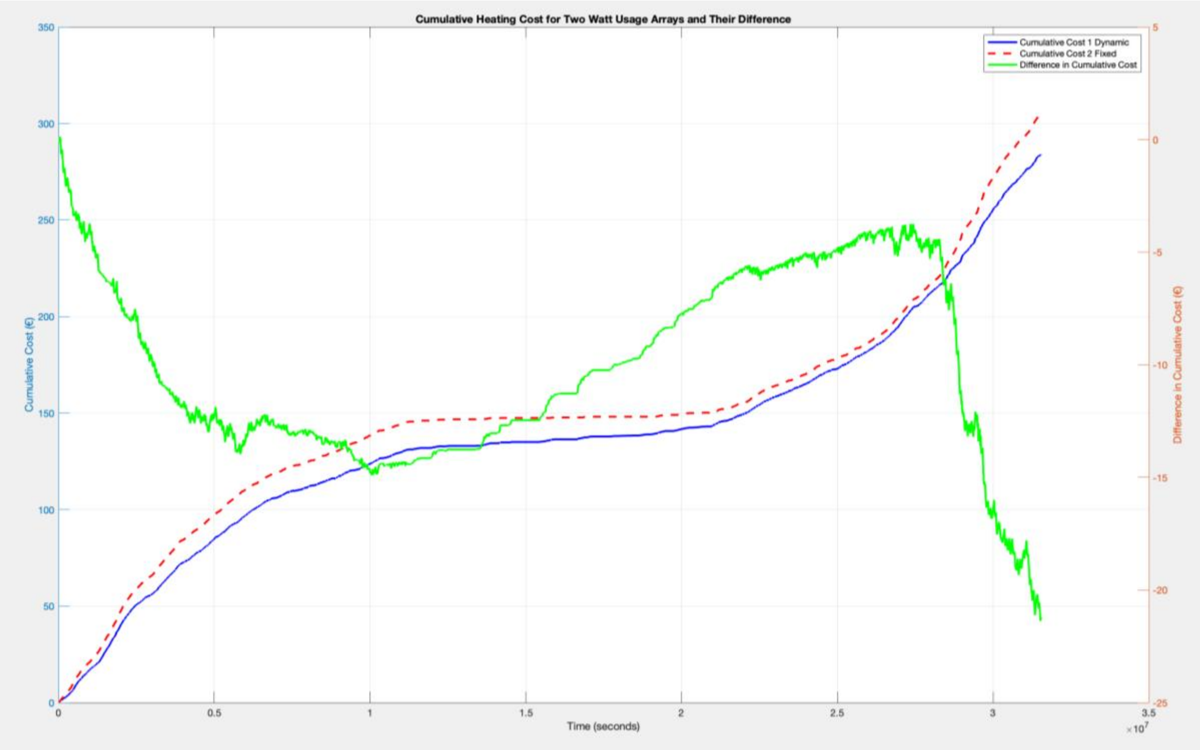
2016: Costs: -9,72%, Output: +2,63%

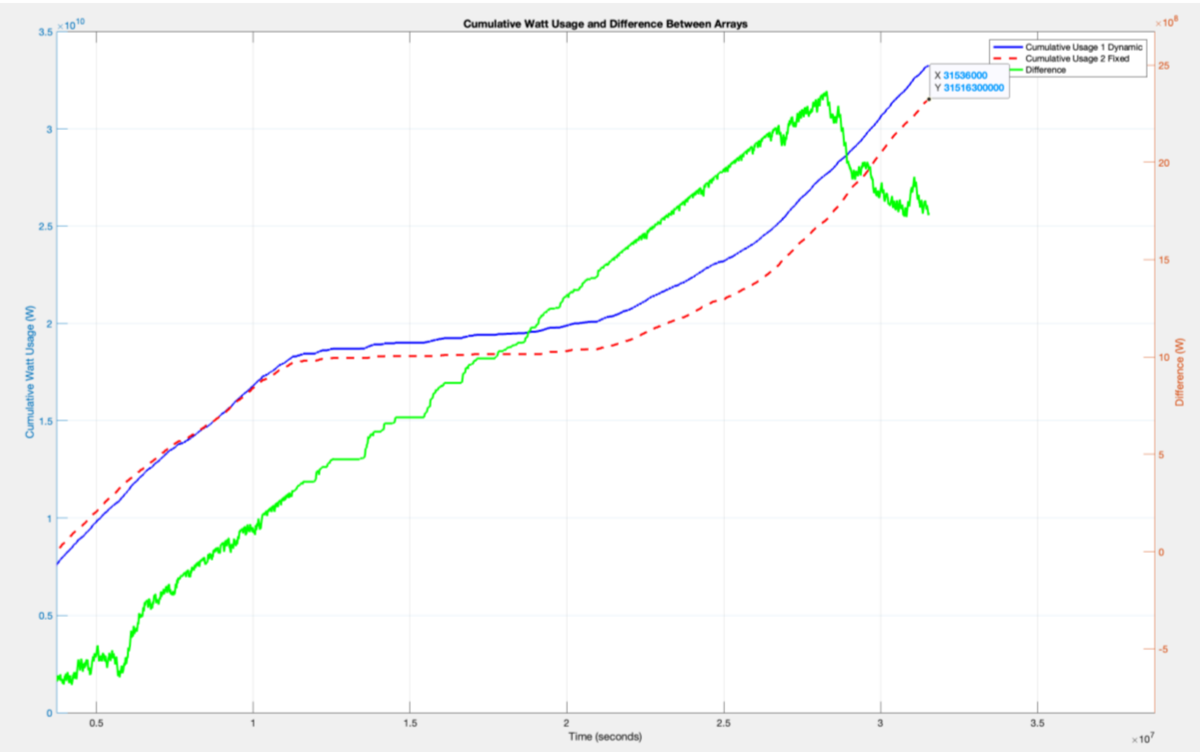




Figures 43 & 44

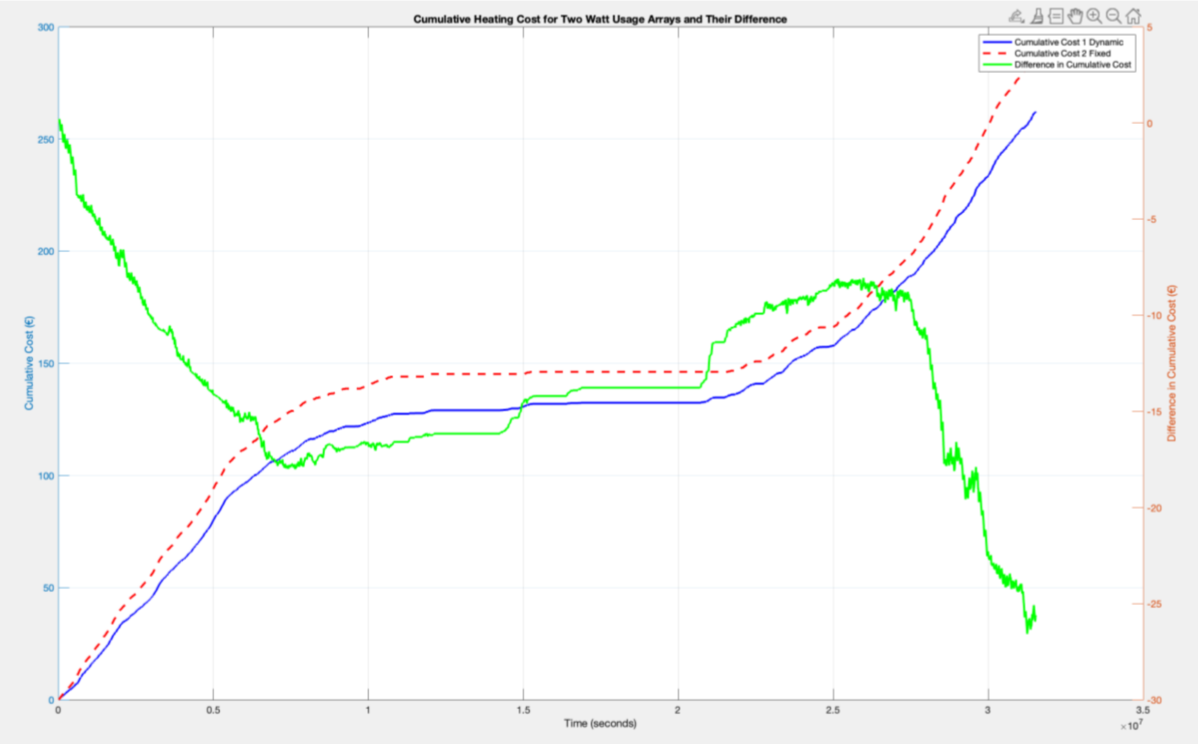
2017: Costs: -6,96%, Output: +5,51%

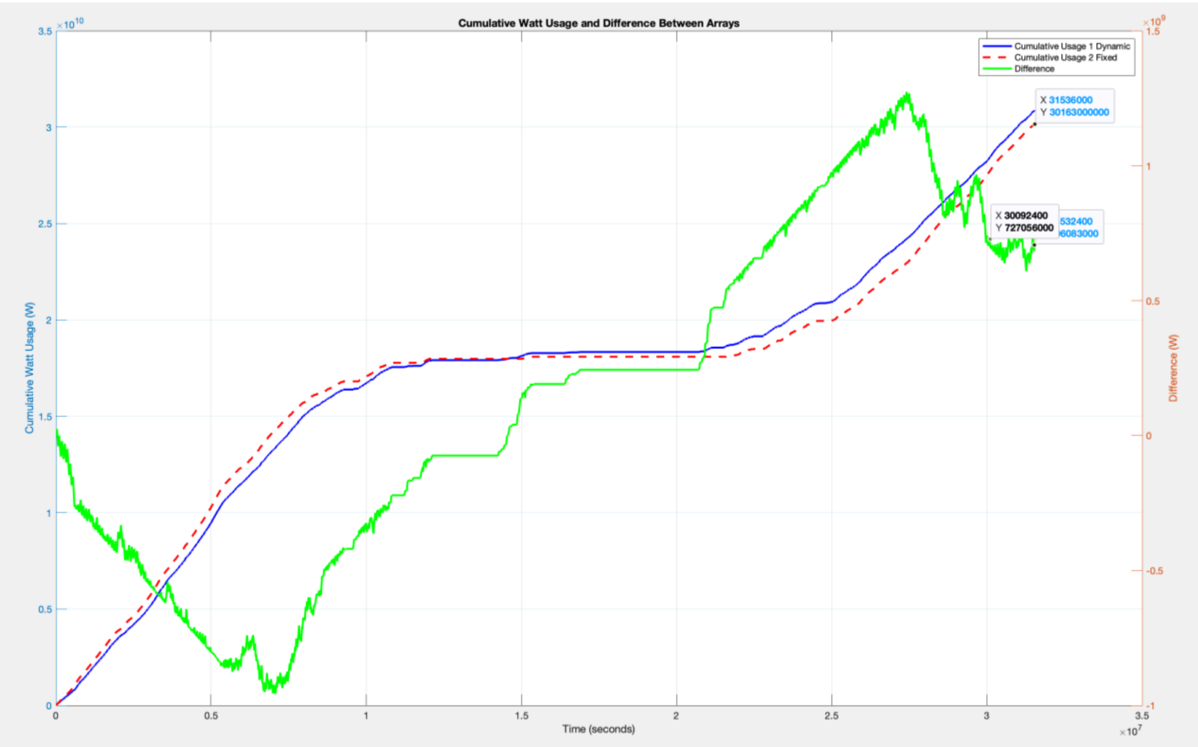




Figures 45 & 46

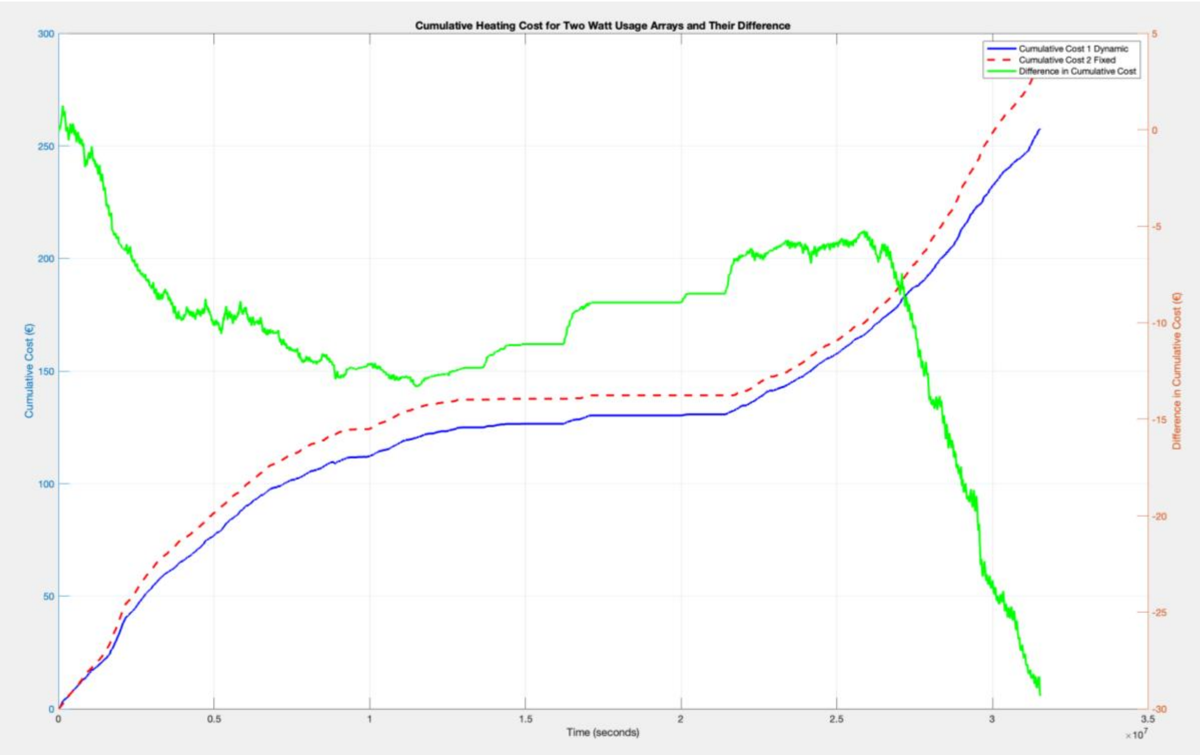
2018: Costs: -8,91%, Output: +2,32%

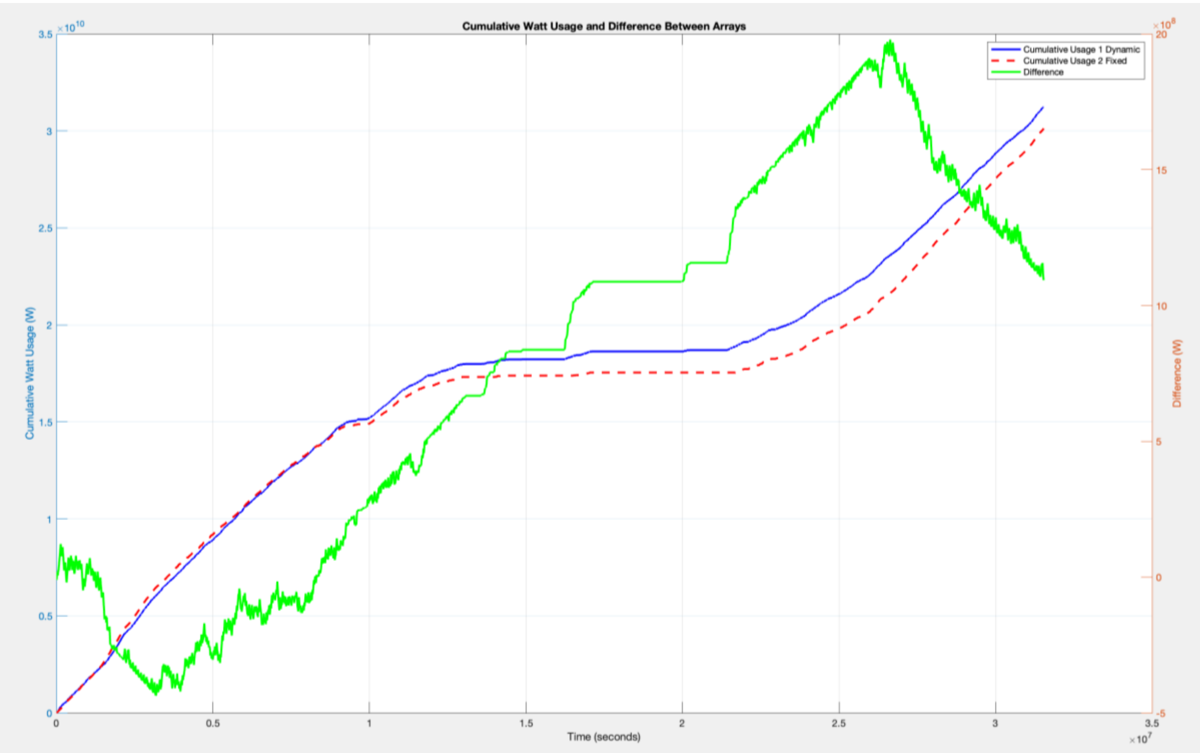




Figures 47 & 48

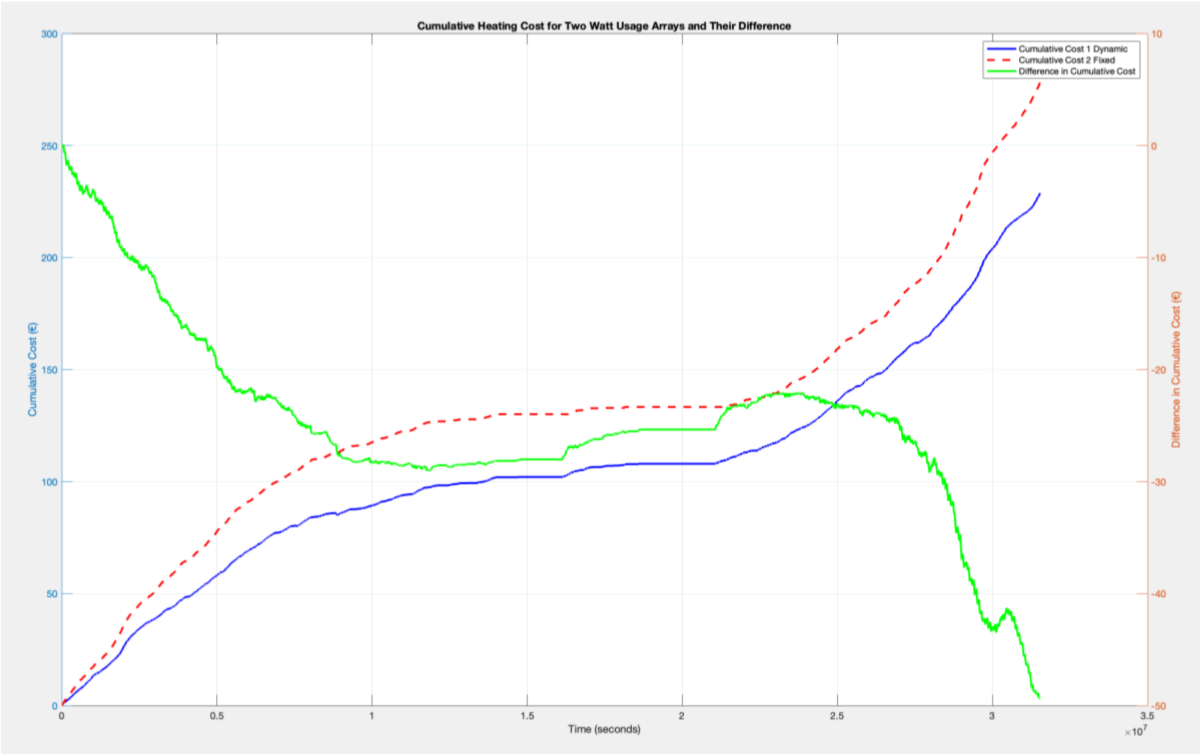
2019: Costs: -10,20%, Output: +3,62%

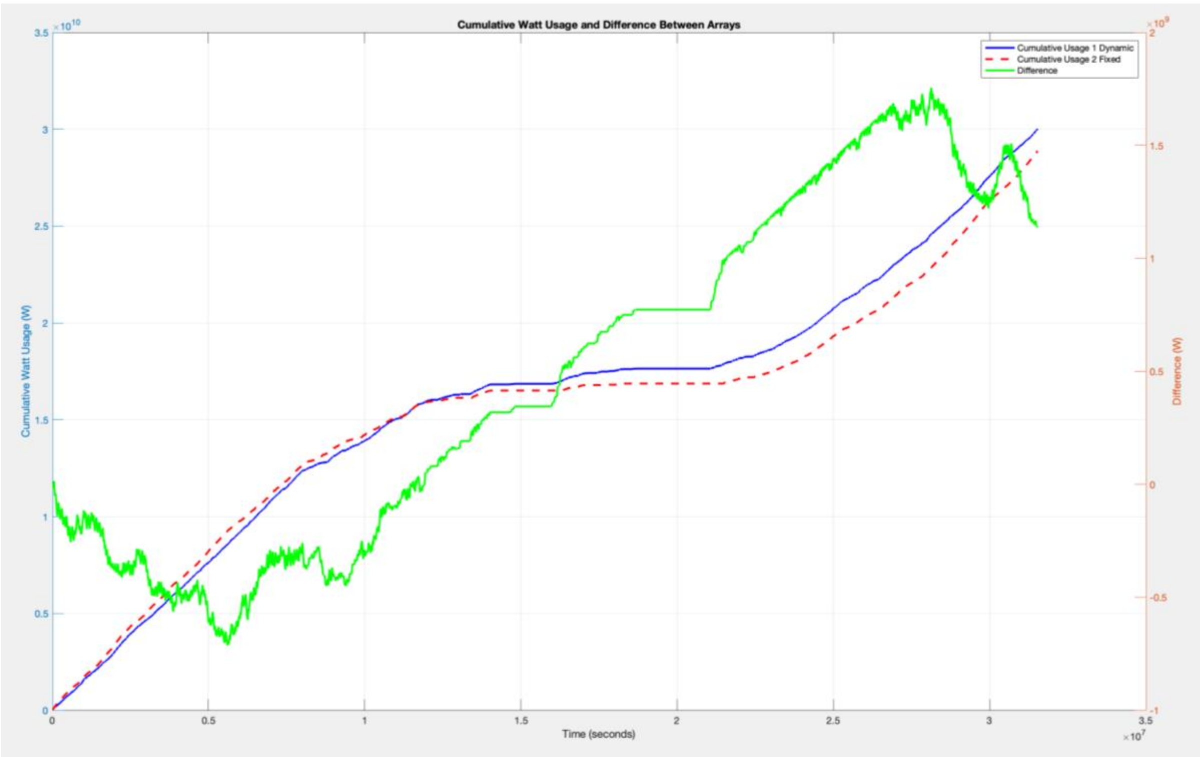




Figures 49 & 50

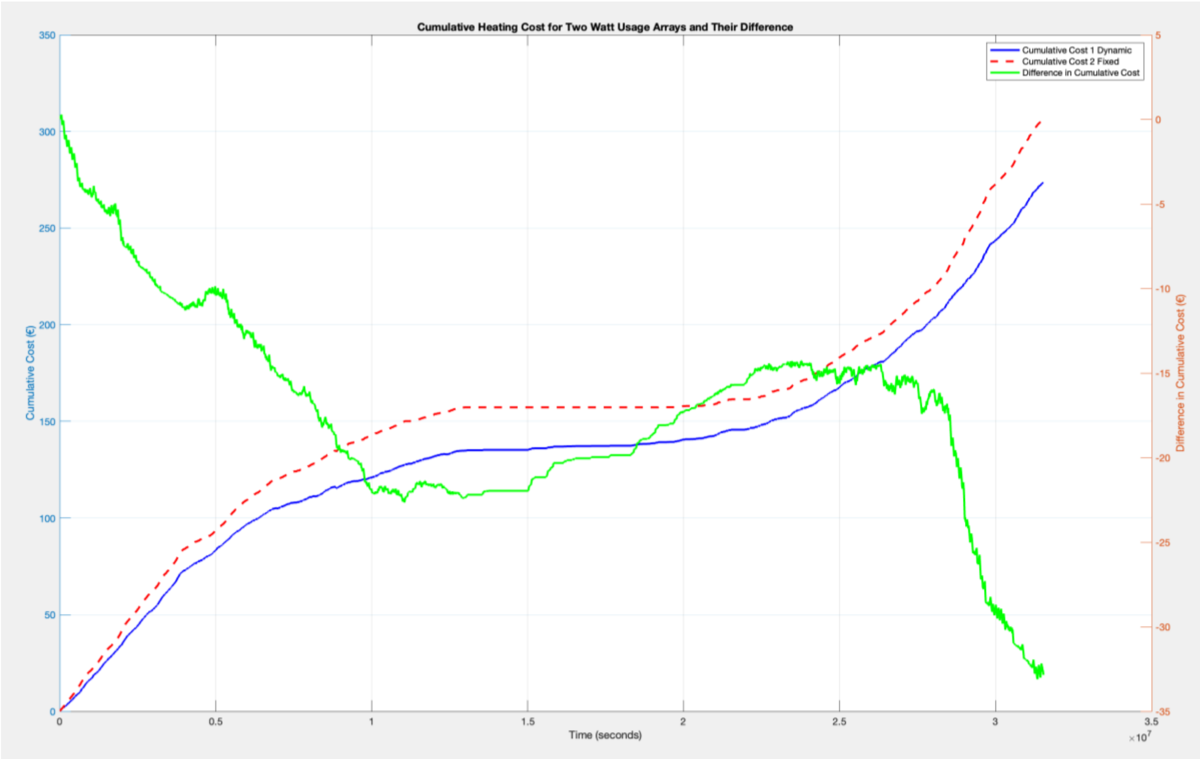
2020: Costs: -17,75%, Output: +3,34%

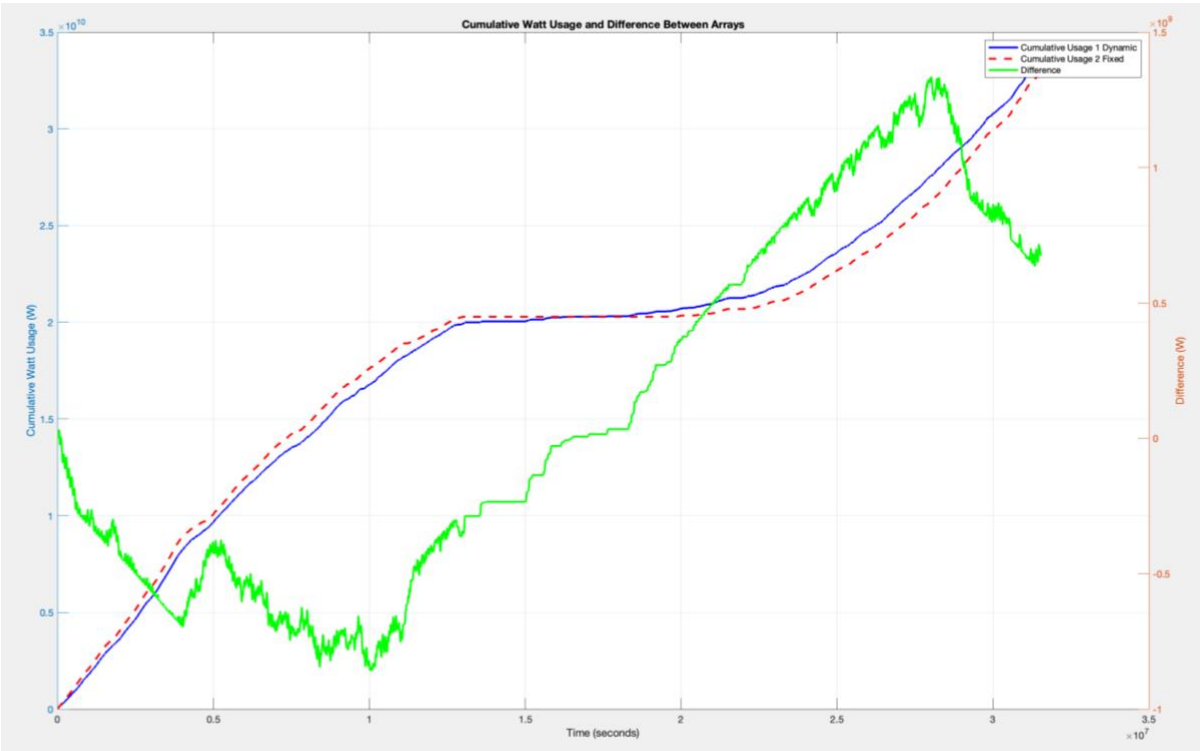




Figures 51 & 52

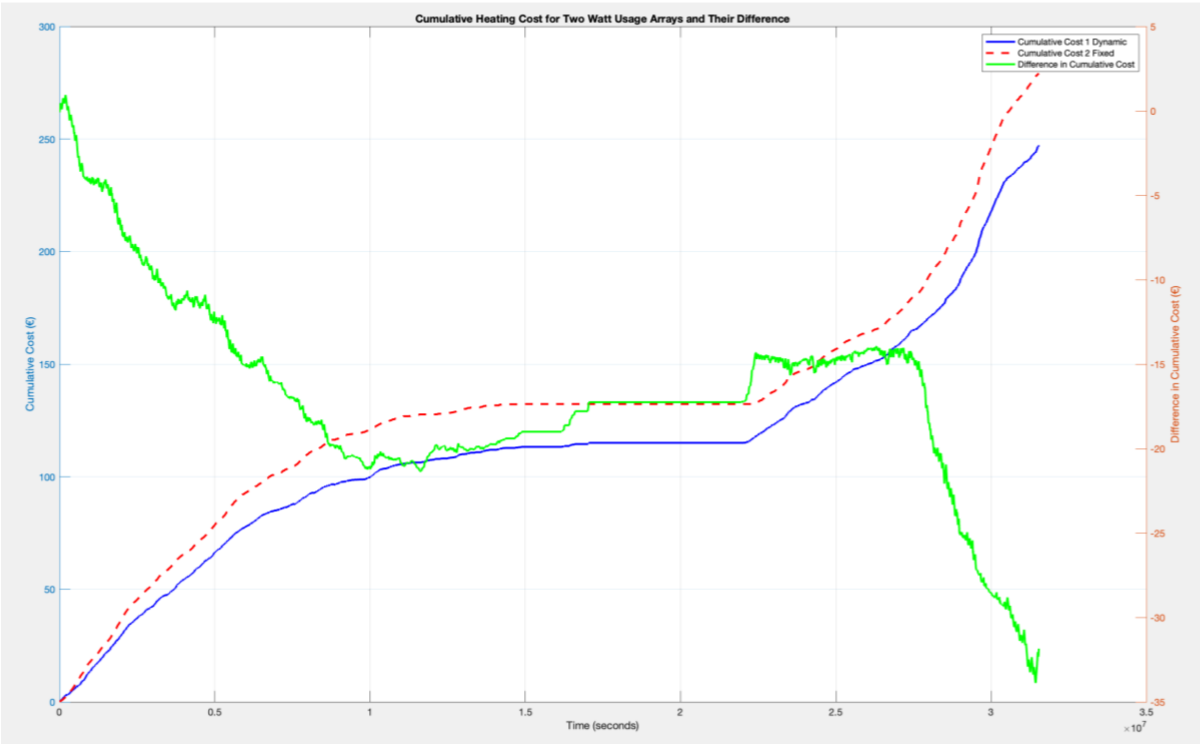
2021: Costs: -10,73%, Output: +2,05%

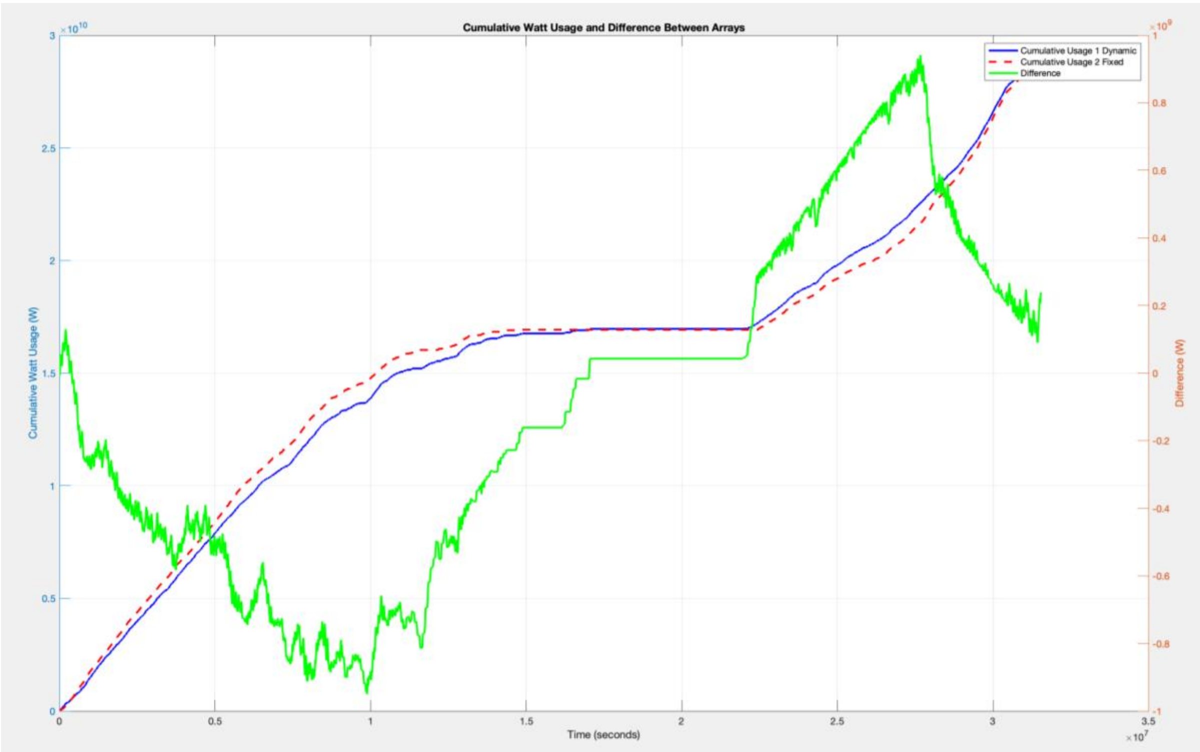




Figures 53 & 54

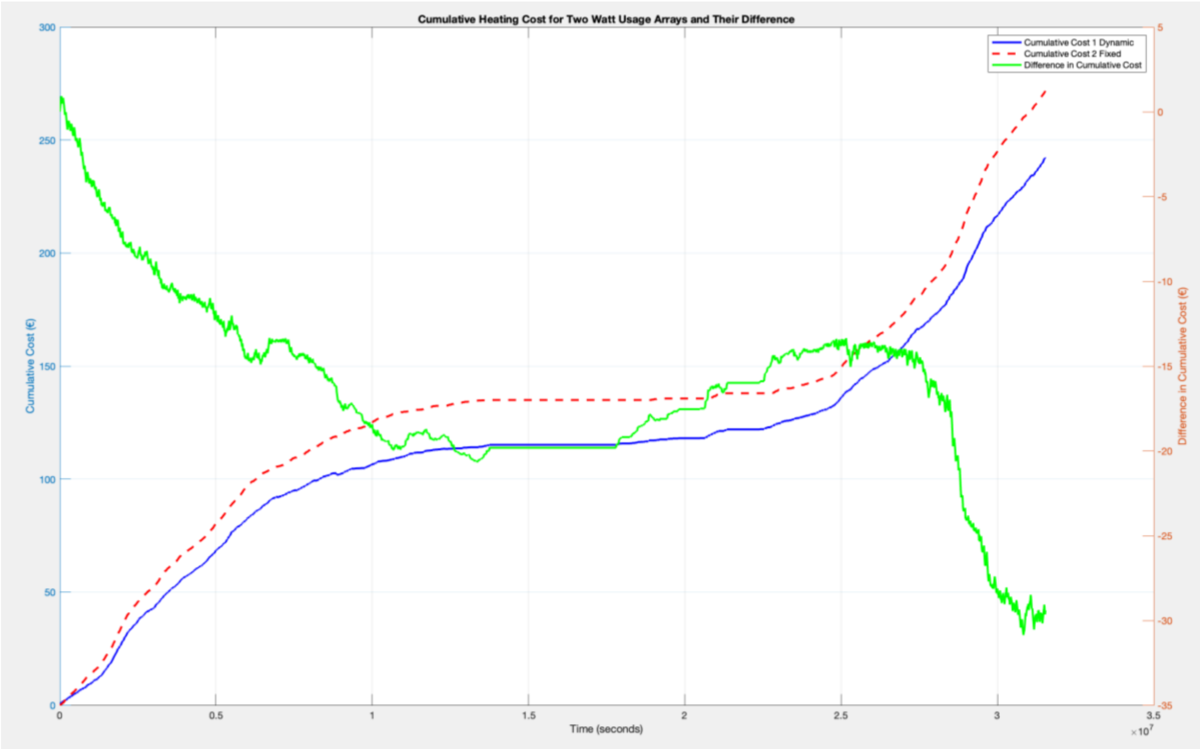
2022: Costs: -17,59%, Output: +0,81%

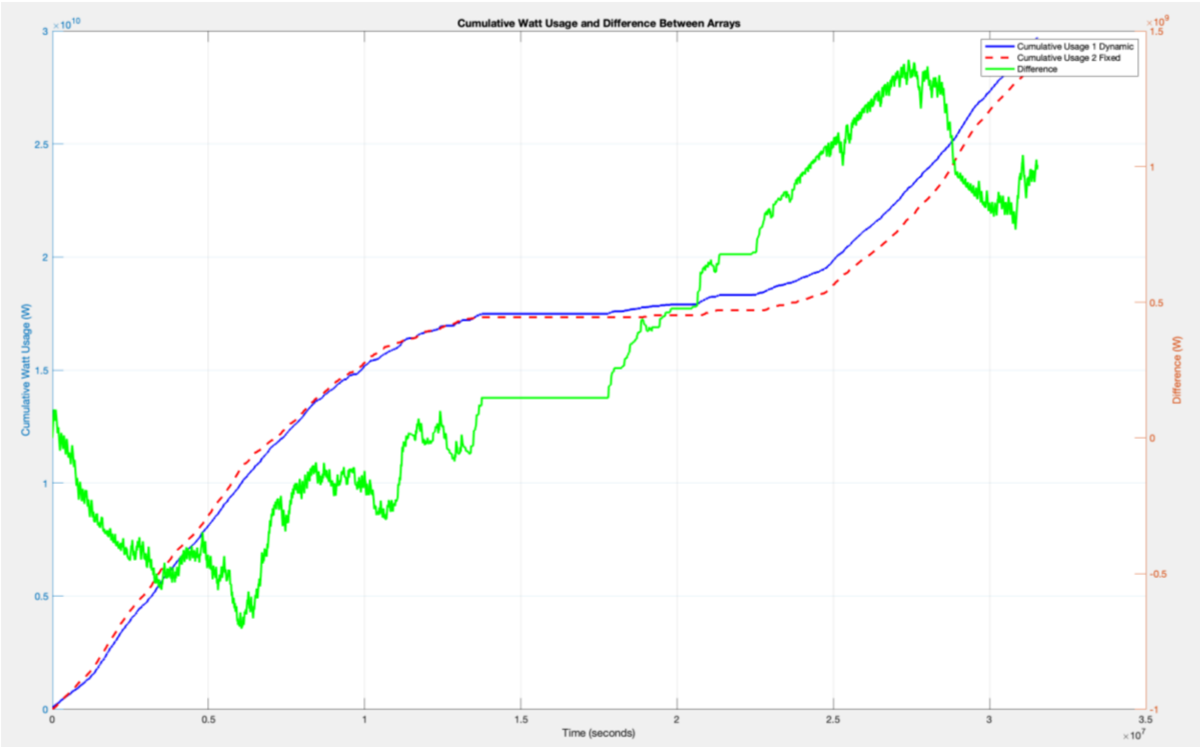




Figures 55 & 56

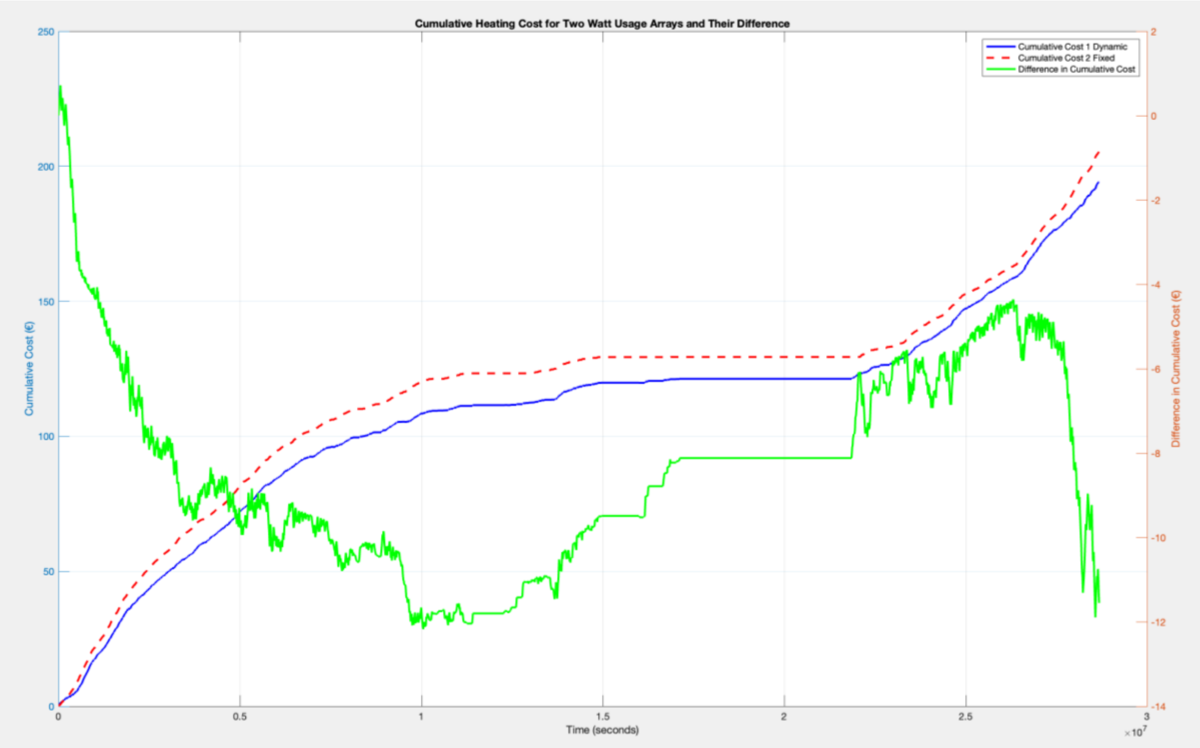
2023: Costs: -10,79%, Output: +3,51%

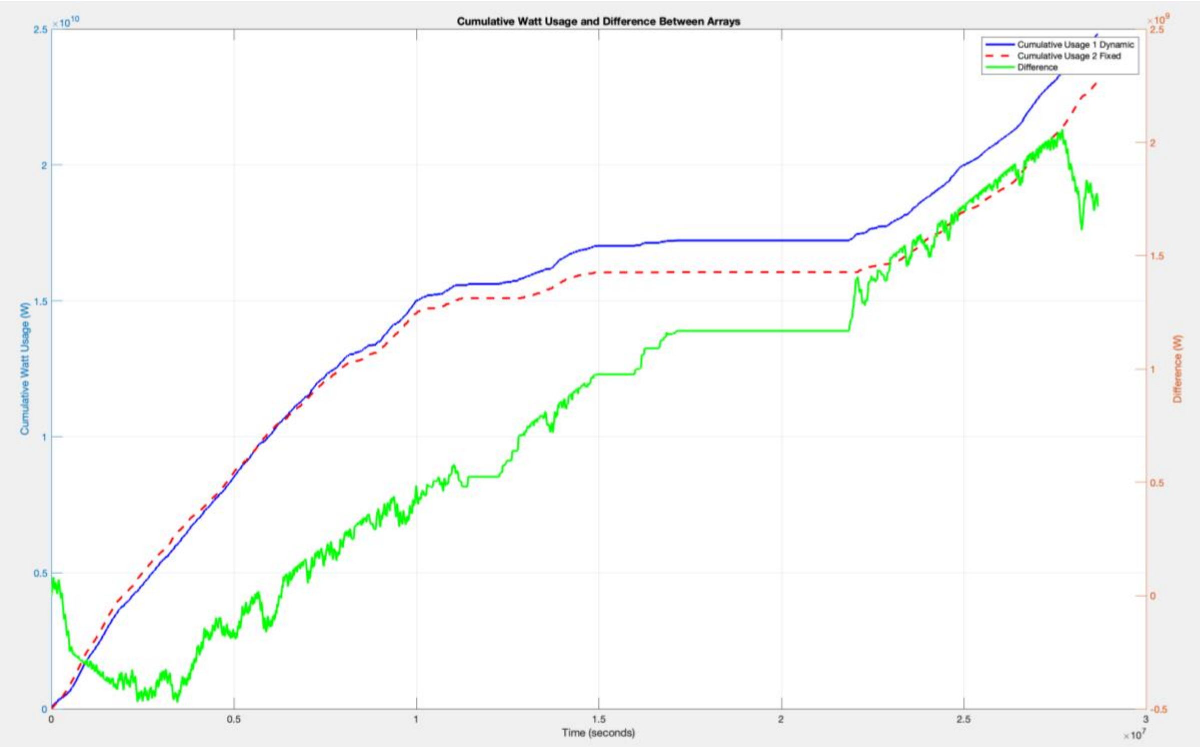




Figures 57 & 58

2024: Costs: -5,56%, Output: +7,38%





Figures 59 & 60

Appendix F. Bandwidth Thermostat Simulation Coding

Find the full code attached as a separate document. Heating logic is visible in the flowchart in Chapter 5. Data sources are referenced and open-source.

Appendix G. Interface Ideation (Additional)

The morphological chart (Figure 61) is employed to explore and compare interaction and communication methods. This allows systematic evaluation and iteration. For this, the core of the interface is determined to be a temperature indicator that ranges across multiple values, a performance graph where a user can see how their bandwidth is helping them, selectable bandwidth sizes, social cues of collaborative performance and a system state representation to communicate operation to the user.

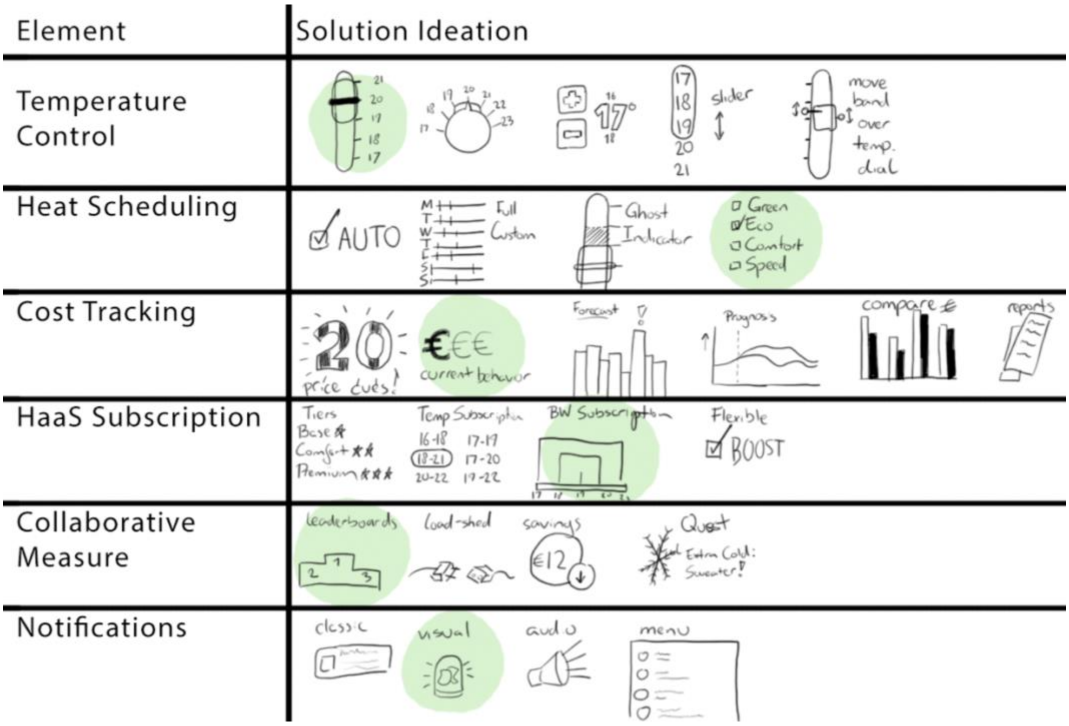


Figure 61

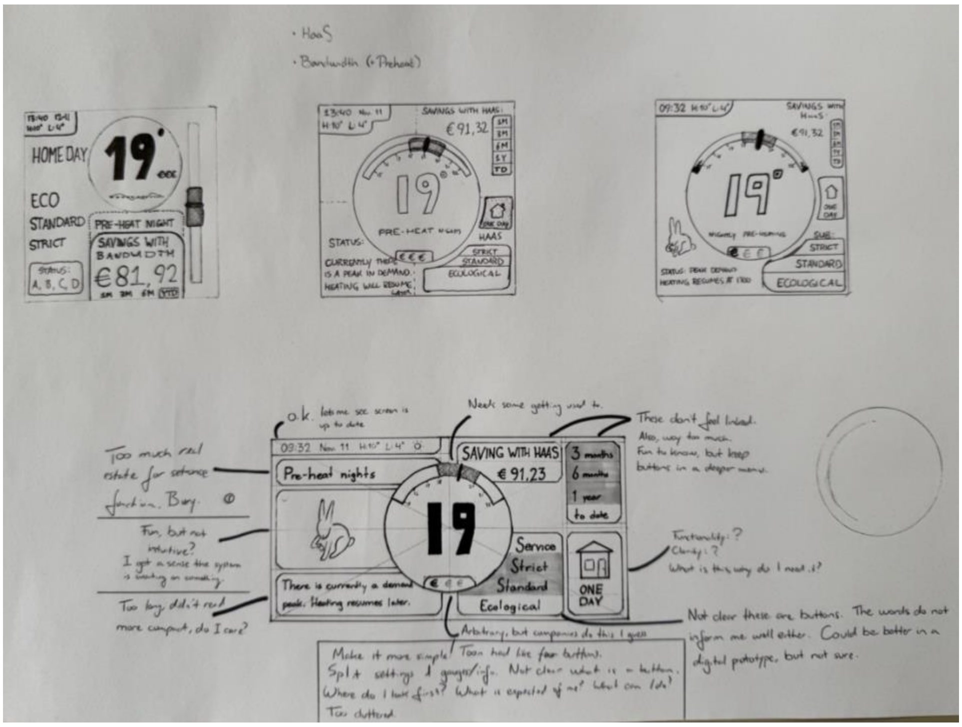


Figure 62

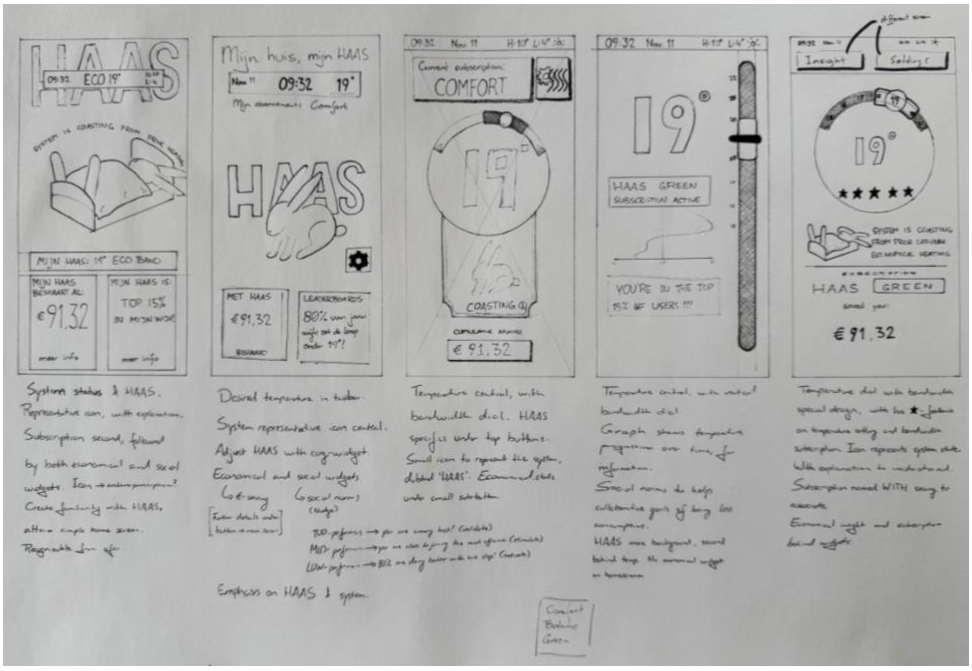


Figure 63

Appendix H. A/B-Test Paper Prototype

The A/B test aims to discover whether the development of the interface should follow the path of a mobile application or stay with the more conventional wall-mounted device. The test is conducted with a paper prototype, that resembles a basic version of the interface at this point (Figure 64**)**.

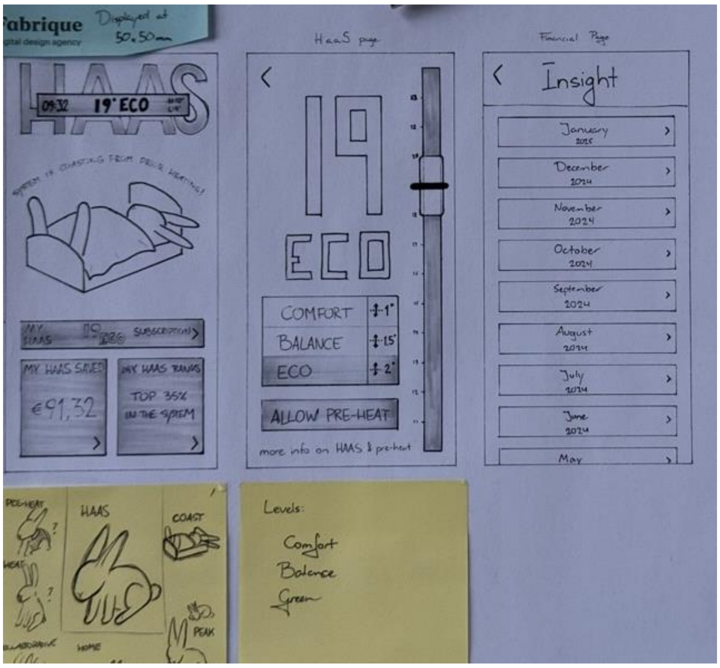


Figure 64: The paper prototype was used with a cardboard cutout to 'switch' screens after pressing a button

The mobile application is referred to as A. The conventional wall-mounted device is referred to as B. Both interfaces are identical, their placement, and thus accessibility, is different. The outcome of this test will determine interface placement in further hi-fi digital prototypes.

Method

- Participants: 8 individuals, aged 23 to 75, asked to rate their own tech proficiency
- 4 participants consider the prototype a phone application (A)
- 4 participants consider the prototype a wall-mounted interface (B)
- Each participant is asked to perform basic tasks (adjusting temperature, assess bandwidth, determine system status, find cost information) using the interface, and asked to explain their thoughts.

Follow-up questions were asked to determine preferences and identify issues.

Participant Profiles

ID	Age	Interface	Tech Proficiency
P1	23	A	High
P2	27	A	Medium
P3	31	A	High
P4	74	A	Medium
P5	67	B	Low
P6	24	B	High
P7	30	B	Medium
P8	59	B	High

Responses

Group A: Phone application

Participant P1 (Age: 23, High Tech Proficiency)

- Main feedback: I appreciate having remote access to my heating system, though if I understand it correctly it is meant to be insightful rather than it requiring my attention. If using it for more of an update I would look for notifications to ensure me it is operating well. I'm not sure about it substituting my thermostat at home.
- Tasks:
    - Adjust temperature: Completed quickly, home screen missclick.
    - Assess bandwidth: Completed, spent time searching on home screen.
    - Determine system status: Completed, acknowledged icon as representation quickly.
    - Find cost information: Completed, quickly found the right button.
- Ease of use: Some refinement needed, but a good prototype.

Participant P2 (Age: 27, Medium Tech Proficiency)

- Main feedback: I understand the accessibility of creating an app, but I do not like having yet another app to dig through on my phone. I would look into having both a thermostat and an application. If the system is as hands-off as it seems, the application would be less of an issue but conversely it would rarely be used.

- Tasks:
  - Adjust temperature: Completed quickly.
  - Assess bandwidth: Completed quickly, misunderstood the bandwidth button itself.
  - Determine system status: Completed quickly, appreciated explanation above icon.
  - Find cost information: Completed quickly.
- Ease of use: It is easy to navigate, though the button labels are not entirely intuitive.

Participant P3 (Age: 31, High Tech Proficiency)

- Main feedback: I like the access I have to my heating system, for example when at work. Especially the ability to have quick insight into what the system is doing is nice, maybe some more insight into active savings per day could be nice. The interface is not yet entirely intuitive, I understand the icon but the buttons or their labels don't give me enough information to understand where they could lead me.
- Tasks:
  - Adjust temperature: Completed, some searching required.
  - Assess bandwidth: Completed, did not understand functionality.
  - Determine system status: Completed, understood icon.
  - Find cost information: Completed quickly.
- Ease of use: Okay for an early prototype, advice is to refine interface. Appreciate the mobile access.

Participant P4 (Age: 74, Medium Tech Proficiency)

- Main feedback: I could probably familiarise to the app, but in this moment I feel like my phone would play too important a role as the sole access point to my heating system. My current heating system can be accessed through an app, but the reality is that I rarely use it; I prefer the thermostat. Also, if I lose my phone I lose access to my heating system. I like that the icon shows me my system is working. 'How does my heating system rank' I don't understand; does it need my attention?

- Tasks:
    - Adjust temperature: Complicated, tried to press the number instead of seeing the slider.
    - Assess bandwidth: Completed, saw the slider as a bandwidth indicator.
    - Determine system status: Completed, icon is easy to understand.
    - Find cost information: Complicated, did not understand button to be a button.
- Ease of use: Difficult to navigate, maybe it takes a learning curve?

Group B: Wall-mounted device

Participant P5 (Age: 67, Low Tech Proficiency)

- Main feedback: I like the rabbit to show me what the system is doing, and I can see it even when I am not standing next to the device. I don't understand exactly what bandwidth does for me, but the 'savings' showed help me. I don't know what 'My Haas ranks 35%' means. If the system works for me I like it, but I don't understand the interface very well.
- Tasks:
    - Adjust temperature: Complicated, needed some explanation.
    - Assess bandwidth: Complicated, adjusted button but did not understand it.
    - Determine system status: Completed, noted the system is probably 'resting'.
    - Find cost information: Complicated, did not see it was a button.
- Ease of use: Difficult buttons, but if it works for me I would only ever look at the rabbit from time to time.

Participant P6 (Age: 24, High Tech Proficiency)

- Main feedback: A wall-mounted device seems somewhat outdated, but in its conventional appearance it does feel familiar. Can I access settings or information from my phone? *[No.]* That would be a nice addition. I like the clean interface, should be refined with further prototypes. Useful, I like its appearance.

- Tasks:
  - Adjust temperature: Completed quickly, quickly jumped through menus and buttons to find.
  - Assess bandwidth: Completed quickly.
  - Determine system status: Completed quickly.
  - Find cost information: Completed, but thought the label was a display instead of a button.
- Ease of use: Good, few mistakes can be made with few buttons. Clean it up to make it better; some better indications and color contrasts could better give feelings of what is a button and what isn't.

Participant P7 (Age: 30, Medium Tech Proficiency)

- Main feedback: The icon is reassuring that the system is actively working, it is kind of similar to a thermostat. Perfect for me, I like hands-off things. Also that the buttons already show important information without having to dig through another screen. Could be nice to show the information showed in the button in the underlying menu, next to the additional info. I don't understand 'ranking in system'; why do I care? Isn't the system always doing its best? I like the info bar above; it promises me that the device hasn't crashed or stopped working because I can see the time.
- Tasks:
  - Adjust temperature: Completed quickly.
  - Assess bandwidth: Completed quickly.
  - Determine system status: Completed quickly.
  - Find cost information: Complicated, thought to see graphs and charts instead of monthly splits.
- Ease of use: Cool! I'm comfortable using it.

Participant P8 (Age: 59, High Tech Proficiency)

- Main feedback: I like things that are simple, sleek and don't demand my time. The fact that I can view status with a quick glance and the system works for me is nice. I hope it really does benefit me, the heating as a service thing. I think I don't want to be thinking about my heating system during the day, so I'm glad this runs on its own. I don't want to read about my costs and such on a wall-mounted device; I expect this to go to my phone or laptop.
- Tasks:
    - Adjust temperature: Completed.
    - Assess bandwidth: Completed quickly.
    - Determine system status: Completed quickly.
    - Find cost information: Complicated, expected an email separate from the device.
- Ease of use: I like it, with a bit more refinement I'm sure I would use it.

Insights

Group A

Participants noted how they do not lean positively towards an application (P1, P2, P4). Participants with self-indicated high tech proficiency appreciate remote access (P1, P3).

Participants with lower self-indicated tech proficiency express reluctance to the phone being their sole access point (P2, P4).

Group B

Participants noted the device felt familiar (P6, P7).

Participants expressed interest in perhaps integrating mobile access (P6).

Participants with self-indicated lower tech proficiency prefer systems that require less interaction (P5).

Participants with self-indicated higher tech proficiency appreciate appreciate a simple and clean interface (P6, P8).

Results

Participants noted the icon as being insightful (P1, P4, P5, P7, P8).

Participants noted that button labels are confusing (P2, P4, P6, P7).

Participants value the hands-off system (P2, P4, P7, P8).

Participants noted to not understand the system ranking social cue (P4, P5, P7).

Participants that are younger or with a higher self-indicated tech proficiency valued some phone integration (P1, P3, P6).

Participants with a lower self-indicated tech proficiency or older age are sceptical of the application or value the familiarity of a wall-mounted device (P2, P4, P6, P7).

Themes

Group A Phone application:

Pro: Flexible, remote, modern.

Con: Another app, reliance on phone.

Group B Wall-mounted device:

Pro: Simple, familiar, sleek.

Con: Feels outdated, limited access.

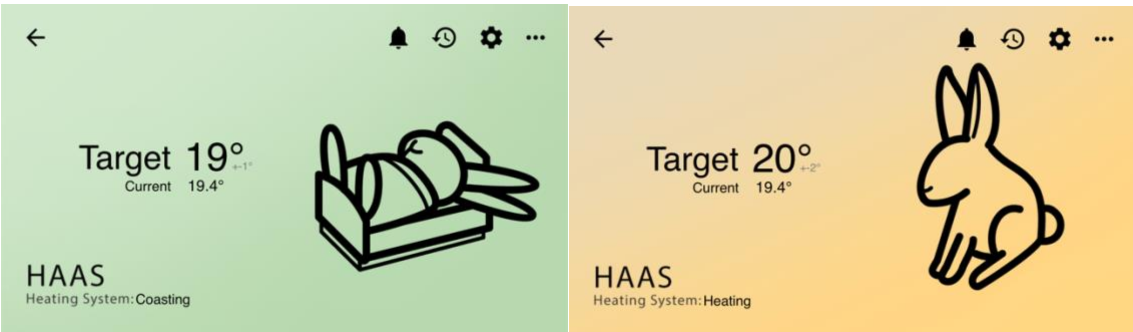
Recommendation

The primary recommendation from this test is to develop a wall-mounted interface as a primary path as the core interface, but to keep open the possibility for phone integration further along in development as a means to include remote access or insight. The wall-mounted interface speaks to the larger pool of participants.

It is possible this test and these participants do not represent the larger population of users. Upon further development this test could be revisited to assess preferred interface hosting device.

Appendix I: Digital Concept Development Additional

Figures 65, 66, 67: The first digital prototype is the initial culmination from earlier paper models. It offers a functional preview of the interface. It features multiple screens, an avatar reflecting system states, and basic click menus that allow users to navigate between different screens. This prototype closely resembles the earlier paper prototype, demonstrating the transition from physical to digital design while keeping desired functionalities. Here, the temperature selector is an array of numbers that require clicking to move the bandwidth.



Figures 68, 69: In this refined digital prototype, the design has evolved to resemble a display on a hosting device and turned horizontal. While it retains similar menus from the previous iteration, the interface has been made more attractive. The screen hue adjusts based on system state changes. The avatar plays a more central role, with other elements moved to menus behind icons to reduce clutter.

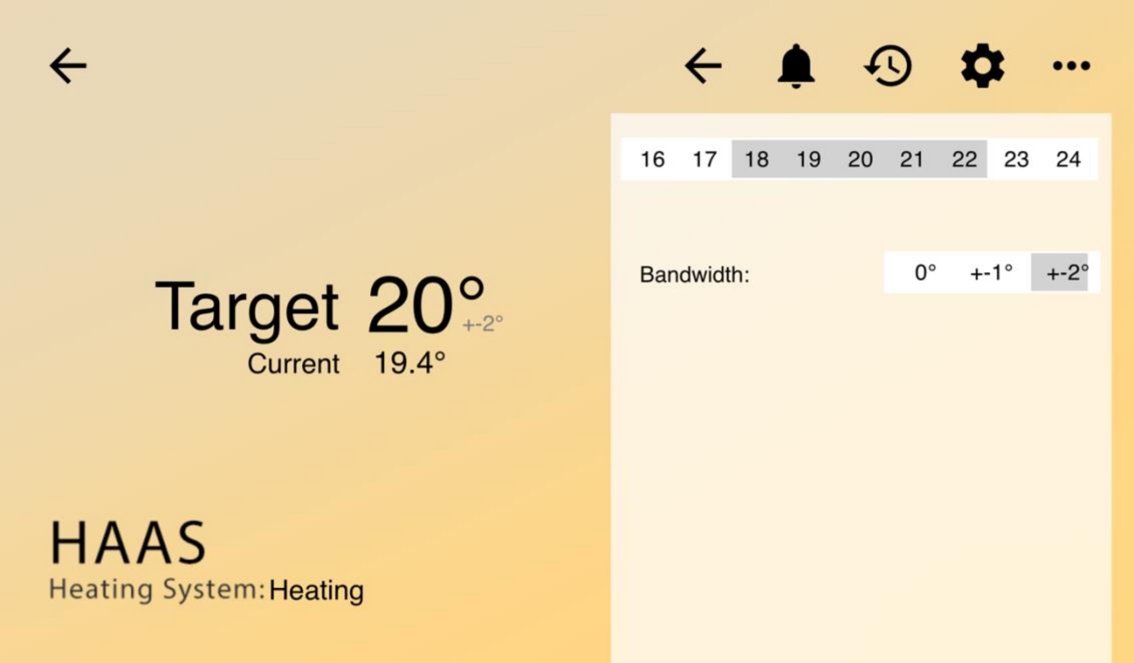


Figure 70: This iteration includes adjustments in bandwidth size, the temperature selector adjusts size to include this bandwidth change.

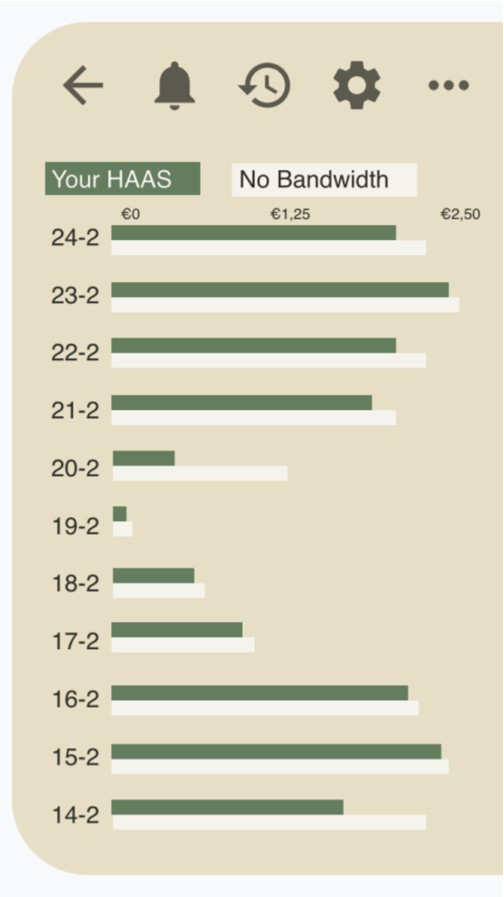


Figure 71: A next iteration includes a bar graph to convey bandwidth savings, comparing it with a fictional calculated equivalent for a fixed thermostat.

Appendix J: Interface Prototype - User Test Sheets

Information Participant 1

Age: **27**
Tech Proficiency (Low/Medium/High): **Medium**

Pre-Test Exploration (1 minute)
Prompt: "Take a minute to explore the system. What do you think this system does?"
Response: "*It looks like a thermostat that lets me control temperature with a type of range dial. The bunny looks like it communicates what the system is doing. I read that it is called bandwidth heating, I also see the past days my heating is cheaper with it. I assume HAAS is the name for my heating system?*"

Task-Based Interaction
Task 1: You just moved into a new home with this heating system. Set up the system to your preference, considering all parameters.
Observations: Participant taps the widget. The participant explores the buttons to see how the range dial changes. From prior exploration participant knows to lean into bandwidth heating for costs. Verbal: "*I assume the bandwidth is lower costs. Two degrees off target does seem too much for my comfort.*" Sets bandwidth to ±1°. Lowers temperature to 18°, confirms her choice.

Task 2: Generally, you like the temperature of your home, but tonight you feel just a bit too cold. What do you do?
Observations: Participant thinks, without actions first. "*I think that maybe it is because the bandwidth could be too big, I would make it smaller*", and adjusts the bandwidth to OFF. Looks at notifications for update, is informed this simulation does not support this. "*Is there a way to adjust this temporarily? I want to go back to original settings after a while.*".

Task 3: You are going on a vacation for one month. What do you instruct your heating system to do in this time?
Observations: Explains: "*What I always do is leave it as low as possible, so it is not used in summer and it does not freeze in winter. Because of course comfort does not matter when I am not there, I choose maximal because the system says it is cheaper.*" Sets temperature to lowest setting available, 8°, and bandwidth to ±2°. "*I can't find a vacation mode.*" Confirms choice.

Task 4: You want to reduce your heating bill without compromising on comfort. What do you do?
Observations: "*Well it is always a compromise I feel, but if trying to save money I think I would increase range. Lower temperature range is okay, but I do not want the system to strive for a lower average temperature I think.*". Participant adjusts heating to 18°, prior desired setting, and ±2° bandwidth.

Post-Test Survey (Qualitative Questions)
How did you decide on your bandwidth settings?
Response: "I feel setting a thermostat to a constant 17° would be too cold for me, but including 17° in a temperature range is probably the coldest I accept. I always try to minimize costs, I would say I'm more of an extra-sweater person rather than a heating person."

Did you feel in control over your heating? Why or why not?
Response: "Yes, I program it right? So I am in control."

What was not clear about bandwidth heating adjustments?
Response: "Well the difference it makes, I don't know. Is ±2° really much better than ±1°? Or is the difference not as much?"

Would you trust this system to optimize heating for you? Why or why not?
Response: "Yes, I think I understand it enough. I would keep an eye on it for the first weeks maybe, to make sure I am familiar with what it does. But I don't want to think about heating really, so I'm sure in the future I would not look at the thermostat nearly as often. Maybe once at the start of winter, and once when spring comes and I turn it off."

Was there a moment where you felt confused? What caused it?
Response: "In the lowering costs task, I am not sure if I did it right. I decide based on comfort, not sure about the effects of lower temperature versus wider range."

Would you be open to using such a system in your life? Why or why not?
Response: "If it works as it says, and it saves money and I can forget about it most of the time: absolutely."

Post-Test Survey (Quantitative Questions, Rate from 1-10, where 1 = Strongly Disagree, 10 = Strongly Agree)

The system is intuitive: 7
The system avatar is intuitive: 7
I feel confident using this system and understand how it works: 5
I agree with bandwidth heating hovering around my desired temperature if I save money: 9
I trust this system to not require my intervention: 6

Additional Notes: Participant noted in task 2, that perhaps a sweater could also alleviate issues but due to the test being aimed at the interface it was instinctive to adjust a setting. Participant looked for some automatic settings for modes such as 'vacation'. Cost-saving was noticed by participant, but not entirely understood in its intricacies with varying temperatures and bandwidths.

Information Participant 2

Age: **24**
Tech Proficiency (Low/Medium/High): **Low to Medium**

Pre-Test Exploration (1 minute)
Prompt: "Take a minute to explore the system. What do you think this system does?"
Response: "*I see some kind of thermostat. I'm not sure... I see some cost stuff. I am not sure, maybe it means that the temperature is somewhere in the white dial blob*."

Task-Based Interaction
Task 1: You just moved into a new home with this heating system. Set up the system to your preference, considering all parameters.
Observations: Participant hesitates to touch interface. Clicks, turns off bandwidth. "*Oh, does the system not heat now? The bunny says no bandwidth.*". Turns bandwidth on. Sets temperature to 17°, ±1°. "*Like this?*", unsure.

Task 2: Generally, you like the temperature of your home, but tonight you feel just a bit too cold. What do you do?
Observations: "*I live in a student home, we have a rule at home that we don't touch the heating because we don't want to pay too much. Honestly I would just look for a sweater and tea.*" Participant does not adjust anything.

Task 3: You are going on a vacation for one month. What do you instruct your heating system to do in this time?
Observations: *"Well my housemates are often home at different times when I am on vacation. So I think also here I would not adjust anything. Of course if no one is home, we would go colder."* Participant does not adjust anything.

Task 4: You want to reduce your heating bill without compromising on comfort. What do you do?
Observations: *"Oh, even colder? I don't think we would like even colder."* Participant views information menu, "Maybe a bigger bandwidth then." Participant adjusts to ±2°.

Post-Test Survey (Qualitative Questions)
How did you decide on your bandwidth settings?
Response: *"I left it mostly, because that is what I do in my house. Only when you asked to decrease costs even more I adjusted it, but this is something I would discuss with my housemates really."*

Did you feel in control over your heating? Why or why not?
Response: *"Kind of? I feel like I could adjust things but I am not sure if I did it the best way."*

What was not clear about bandwidth heating adjustments?
Response: *"I don't know how much of a difference my actions make. I feel unsure about my inputs."*

Would you trust this system to optimize heating for you? Why or why not?
Response: *"If it saves us money, yes. But I would take some time to understand it."*

Was there a moment where you felt confused? What caused it?
Response: *"When I had to adjust things I did not feel comfortable in my knowledge of the system. I read that wider ranges save money but was not sure which range to pick."*

Would you be open to using such a system in your life? Why or why not?
Response: *"If I can set it and forget it, save money and understand it better yes."*

Post-Test Survey (Quantitative Questions, Rate from 1-10, where 1 = Strongly Disagree, 10 = Strongly Agree)

The system is intuitive: **4**
The system avatar is intuitive: **5**
I feel confident using this system and understand how it works: **3**
I agree with bandwidth heating hovering around my desired temperature if I save money: **9**
I trust this system to not require my intervention: **6**

Additional Notes: Participant hesitance to interact. Did not entirely grasp the system, which led to some insecurity on their actions.

Information Participant 3

Age: **25**
Tech Proficiency (Low/Medium/High): **Medium**

Pre-Test Exploration (1 minute)
Prompt: "Take a minute to explore the system. What do you think this system does?"
Response: It seems to be some system that manages temperatures, and you can select temperature ranges. The avatar is kind of a representation of system status, nice."

Task-Based Interaction
Task 1: You just moved into a new home with this heating system. Set up the system to your preference, considering all parameters.
Observations: Moves quite quickly through the interface menus. Adjusts temperature to 20°. *"I don't mind a bit of fluctuation, but I'd like it more steady and comfortable*." Refers to avatar while adjusting temperatures, *"It seems the avatar tells me about what the bandwidth is doing with my settings."* Selects bandwidth ±1°.

Task 2: Generally, you like the temperature of your home, but tonight you feel just a bit too cold. What do you do?
Observations: Immediately increases temperature of home by adjusting temperature dial, and turns off bandwidth. *"Without the bandwidth I force the system to heat, right?".*

Task 3: You are going on a vacation for one month. What do you instruct your heating system to do in this time?
Observations: Clicks in the temperature dial to lowest possible setting, bandwidth changed to ±2°. *"If I select a big bandwidth even lower temperatures are allowed, so that sounds like it makes sense to do on vacation. I don't mind as much about cost savings as about being sustainable, the system doesn't tell me whether bandwidth heating is sustainable."*

Task 4: You want to reduce your heating bill without compromising on comfort. What do you do?
Observations: *"Okay, the system tells me bandwidth is cheaper. So I increase bandwidth."*

Post-Test Survey (Qualitative Questions)
How did you decide on your bandwidth settings?
Response: *"A bit of fluctuation is okay, but I like a steady temperature. Also because I value sustainability more than economical heating (the system does not tell me if it is sustainable), I landed halfway with ±1°."*

Did you feel in control over your heating? Why or why not?
Response: *"Sure. I turn bandwidth on when I want it and off when I want it. Avatar did help confirm system state to me."*

What was not clear about bandwidth heating adjustments?
Response: *“Not a lot really, in this concept I understand how cost reduction applies.”*

Would you trust this system to optimize heating for you? Why or why not?
Response: *“Sure, I can see how it would work well in reducing costs. I am interested in how noticeable the temperature changes are in a bandwidth range.”*

Was there a moment where you felt confused? What caused it?
Response: *“No. Explanation and avatar made things clear. In the exploration I grasped the idea.”*

Would you be open to using such a system in your life? Why or why not?
Response: *“Yes, certainly. If I know more about sustainable heating and how that factors in I would love to try this.”*

Post-Test Survey (Quantitative Questions, Rate from 1-10, where 1 = Strongly Disagree, 10 = Strongly Agree)

The system is intuitive: **8**
The system avatar is intuitive: **8**
I feel confident using this system and understand how it works: **8**
I agree with bandwidth heating hovering around my desired temperature if I save money: **6**
I trust this system to not require my intervention: **8**

Additional Notes: Participant seemed confident and explorative. I suspect technical proficiency might be more than medium. Prioritization of comfort, after which sustainability. Costs were a bit lower on their list, and as such seemed to factor less into behavior. More trust could be granted to them with a bit more information.

Information Participant 4

Age: **67**
Tech Proficiency (Low/Medium/High): **Low**

Pre-Test Exploration (1 minute)
Prompt: "Take a minute to explore the system. What do you think this system does?"
Response: "*It is a thermostat, but different. It is in a type of tablet with another menu. It is quite a lot of things at once coming at me.*"

Task-Based Interaction
Task 1: You just moved into a new home with this heating system. Set up the system to your preference, considering all parameters.
Observations: Participant looks for a simple way to adjust the temperature. Clicks on 19°. Does not adjust or acknowledge bandwidth. "*Which temperature in the white indicator is it?*". After reading information page in interface has a better understanding, "*Ah so bigger means I pay less*.". Adjusts to ±2°. "*I can wear a sweater if needed*."

Task 2: Generally, you like the temperature of your home, but tonight you feel just a bit too cold. What do you do?
Observations: *"No I never adjust the temperature! In the evenings I wear a sweater. I am not going to adjust my temperature all the time."*

Task 3: You are going on a vacation for one month. What do you instruct your heating system to do in this time?
Observations: "*For this I would adjust my settings. 12° works for me in winter*." Adjusts temperature to 12°. "*Why isn't this automatic?*"

Task 4: You want to reduce your heating bill without compromising on comfort. What do you do?
Observations: Participant takes some time to read through information page again. "*So lower temperatures and a larger bandwidth works best.*" Adjusts temperature lower and maintains largest bandwidth ±2°. *"The system should tell me this?"*

Post-Test Survey (Qualitative Questions)
How did you decide on your bandwidth settings?
Response: *"I want to save money in the temperature I can still accept."*

Did you feel in control over your heating? Why or why not?
Response: *"I am overwhelmed a bit, but I am starting to understand it. I feel more in control if I understand better what it is I am doing and what the effect is."*

What was not clear about bandwidth heating adjustments?
Response: *"I understand that it saves money. I don't know how comfortable it can be? If the temperature changes? But I would try this."*

Would you trust this system to optimize heating for you? Why or why not?
Response: *"Yes, I think it could do a better job than me. I would like to know more about it."*

Was there a moment where you felt confused? What caused it?
Response: *"Yes, a bit overwhelmed more than confused. I am used to a simple thermostat."*

Would you be open to using such a system in your life? Why or why not?
Response: *"I would want to try it, if it works then I would buy it."*

Post-Test Survey (Quantitative Questions, Rate from 1-10, where 1 = Strongly Disagree, 10 = Strongly Agree)

The system is intuitive: **5**
The system avatar is intuitive: **6**
I feel confident using this system and understand how it works: **3**
I agree with bandwidth heating hovering around my desired temperature if I save money: **8**
I trust this system to not require my intervention: **5**

Additional Notes: The participant prefers simplicity, or is used to it. Expects more from the system in terms of autonomy or advice. Is motivated by cost savings. Participant would have liked more reassuring information or advice.

Information Participant 5

Age: **74**
Tech Proficiency (Low/Medium/High): **Medium**

Pre-Test Exploration (1 minute)
Prompt: "Take a minute to explore the system. What do you think this system does?"
Response: "It controls heating in a method that is less expensive. It gives some other information about how it operates with bandwidth."

Task-Based Interaction
Task 1: You just moved into a new home with this heating system. Set up the system to your preference, considering all parameters.
Observations: *"I see that bandwidth affects cost, but I don't see anything about being able to choose to optimize for sustainable energy? Or optimize for emission savings?"* Participant chooses 18°, with a ±1° bandwidth. Participant scans information menu, *"I would like to be able to choose on which metric the system optimizes."*

Task 2: Generally, you like the temperature of your home, but tonight you feel just a bit too cold. What do you do?
Observations: Participant decides on turning off the bandwidth heating, does not note avatar. *"I don't want to waste energy, I would rather be able to indicate my preference for being 'cold' in which the system slightly or incrementally adjusts its behavior for a limited time."*

Task 3: You are going on a vacation for one month. What do you instruct your heating system to do in this time?
Observations: For vacations the participants lowers their heating. "*I don't see an option to increase heating to at least reasonable levels from a distance.*" Sets temperature to 10°.

Task 4: You want to reduce your heating bill without compromising on comfort. What do you do?
Observations: Quickly increases bandwidth. *"Why do you only ask about cost reduction? What about energy mixes I may prefer?"*

Post-Test Survey (Qualitative Questions)
How did you decide on your bandwidth settings?
Response: "*I balance comfort with savings because that is what this interface allows*."

Did you feel in control over your heating? Why or why not?
Response: "*No, I think options I am looking for don't exist here*."

What was not clear about bandwidth heating adjustments?
Response: "*How the optimisation affects consumption*"

Would you trust this system to optimize heating for you? Why or why not?
Response: "*If I would want only cost optimisation yes, but in my case it is still missing some functionality*."

Was there a moment where you felt confused? What caused it?
Response: "*Not confused, more frustrated about the design tailored for cost-conscious.*"

Would you be open to using such a system in your life? Why or why not?
Response: *"I am not disinterested in saving money, but if there were a dial to set preference between cost saving and renewable energy use it would appeal to me more."*

Post-Test Survey (Quantitative Questions, Rate from 1-10, where 1 = Strongly Disagree, 10 = Strongly Agree)

The system is intuitive: 8
The system avatar is intuitive: 4 "I don't need it but nice from a distance"
I feel confident using this system and understand how it works: 9
I agree with bandwidth heating hovering around my desired temperature if I save money: 7
I trust this system to not require my intervention: 6

Additional Notes: Participant did not note anything on the avatar. Asked about the choice to choose optimisation metric, or shift prioritization. Demanded more details on the sustainable side of things.

Information Participant 6

Age: **25**

Tech Proficiency (Low/Medium/High): **Medium**

Pre-Test Exploration (1 minute)

Prompt: "Take a minute to explore the system. What do you think this system does?"

Response: *"It controls my heating and is automatically optimizing! I like that it does not require my attention, I am not very interested in heating honestly."*

Task-Based Interaction

Task 1: You just moved into a new home with this heating system. Set up the system to your preference, considering all parameters.

Observations: Moves quickly, instantly clicks on 18°. Notices bandwidth, *"I'm not sure I like the possibility of 17°. Does the system tell me if 19°±1° is better than 18° without bandwidth?"* Leaves settings as is.

Task 2: Generally, you like the temperature of your home, but tonight you feel just a bit too cold. What do you do?

Observations: "*I guess I would let it do its job? But I also don't want to be cold now*." Adjusts temperature to 19°. Does not touch bandwidth.

Task 3: You are going on a vacation for one month. What do you instruct your heating system to do in this time?

Observations: "*I would like a vacation button, so the system automatically adjusts*". Taps the temperature dial to 10°. Does not touch bandwidth.

Task 4: You want to reduce your heating bill without compromising on comfort. What do you do?

Observations: *"Does the system not already do the best it can? I already set it to the lowest temperature I think is acceptable. I wouldn't touch it."*

Post-Test Survey (Qualitative Questions)

How did you decide on your bandwidth settings?

Response: *"I just picked the lowest possible comfortable option."*

Did you feel in control over your heating? Why or why not?

Response: "*Yes, but I don't care to be in control maybe? If the system does its job, saves me money based on my initial input: I'm excited*."

What was not clear about bandwidth heating adjustments?

Response: "*I think I understood it. It is an automatic heating system optimizing costs*."

Would you trust this system to optimize heating for you? Why or why not?

Response: *"Absolutely, that is the whole point of it."*

Was there a moment where you felt confused? What caused it?
Response: *"Not really, not much more than any new product takes getting used to."*

Would you be open to using such a system in your life? Why or why not?
Response: "Yes."

Post-Test Survey (Quantitative Questions, Rate from 1-10, where 1 = Strongly Disagree, 10 = Strongly Agree)

The system is intuitive: 9
The system avatar is intuitive: 7 "*It's fine, I didn't need it really*"
I feel confident using this system and understand how it works: 9
I agree with bandwidth heating hovering around my desired temperature if I save money: 8
I trust this system to not require my intervention: 10

Additional Notes: Strong sense of set-it-and-forget-it, appreciates automatic optimisation. No interest in heating. Appreciates non-intrusiveness.

Information Participant 7

Age: **27**

Tech Proficiency (Low/Medium/High): **Medium**

Pre-Test Exploration (1 minute)

Prompt: "Take a minute to explore the system. What do you think this system does?"

Response: "I'm not sure what the graph shows me; savings, costs, or something else? Some type of temperature setting system, it seems to reduce your costs and show insight."

Task-Based Interaction

Task 1: You just moved into a new home with this heating system. Set up the system to your preference, considering all parameters.

Observations: Opens widget and hesitates. Scrolls through temperatures, "I don't see the direct influence of my choices on energy costs." Chooses ±1°, based on comfort considerations desiring a narrower bandwidth at 18°. "When I'm not home I don't need it to heat?"

Task 2: Generally, you like the temperature of your home, but tonight you feel just a bit too cold. What do you do?

Observations: "I reach for a sweater. Only if this doesn't help I would reach for the heating system. I would then increase the temperature." Did not choose to decrease bandwidth range, OFF seems like you turn off the heating.

Task 3: You are going on a vacation for one month. What do you instruct your heating system to do in this time?

Observations: Turns dial all the way to 8°, no bandwidth. 'OFF' resonates as the most docile mode, without realizing the effect it has. "Is there just an off button? Or vacation button?"

Task 4: You want to reduce your heating bill without compromising on comfort. What do you do?

Observations: Increases bandwidth to ±2°. Retains 19° temperature. "I think that a larger bandwidth leaves more space where the system can optimize."

Post-Test Survey (Qualitative Questions)

How did you decide on your bandwidth settings?

Response: *"I felt like leaving more space for the system (bandwidth) is more optimal. The largest bandwidth feels undesirable from a comfort viewpoint."*

Did you feel in control over your heating? Why or why not?

Response: "I felt in control, but I didn't always feel knowledgable."

What was not clear about bandwidth heating adjustments?

Response: *"The interface is a bit dull, as a result I can't always make sense of what I'm* *seeing and where I should look. It is not clear which effects my bandwidth settings have on my consumption and costs when adjusting it."*

Would you trust this system to optimize heating for you? Why or why not?
Response: *"If I understood it more I would trust it more, but the pitch is good."*

Was there a moment where you felt confused? What caused it?
Response: *"Without instant feedback on my actions it sometimes felt like I wasn't certain my actions had the consequences I desired."*

Would you be open to using such a system in your life? Why or why not?
Response: *"Yes, but with an interface rework. The concept of optimized heating appeals to me."*

Post-Test Survey (Quantitative Questions, Rate from 1-10, where 1 = Strongly Disagree, 10 = Strongly Agree)

The system is intuitive: 3 *"Interface decreases intuition."*
The system avatar is intuitive: 6 "*Could be more expressive to be more intuitive*"
I feel confident using this system and understand how it works: 6 *"The interface does not make me confident, but I see what bandwidth is and what it brings me"*
I agree with bandwidth heating hovering around my desired temperature if I save money: 7
I trust this system to not require my intervention: 7

Additional Notes: Notes that a turn dial is more alike to conventional thermostats, and this digital representation is less familiar. I do not feel certain I understand what I am doing. Participant asks whether asymmetrical bandwidths are possible, the largest bandwidth is too wide to seem comfortable.

Information Participant 8

Age: **54**
Tech Proficiency (Low/Medium/High): **High**

Pre-Test Exploration (1 minute)
Prompt: "Take a minute to explore the system. What do you think this system does?"
Response: *"It manages heating with a bandwidth, it seems like a flexible method of heating. And you can adjust that variation."*

Task-Based Interaction
Task 1: You just moved into a new home with this heating system. Set up the system to your preference, considering all parameters.
Observations: Clicks 18°, no bandwidth. *"So, bandwidth saves me money maybe? What is the tradeoff?"* Decides on ±1°. *"I would like some feedback on my actions, what does bandwidth do for me"*

Task 2: Generally, you like the temperature of your home, but tonight you feel just a bit too cold. What do you do?
Observations: *"Nothing, if I am only a bit too cold I look for a sweater. I set it to 18 and usually that is just fine for me."*

Task 3: You are going on a vacation for one month. What do you instruct your heating system to do in this time?
Observations: "Where is the vacation mode? Hm, if I would do it by hand I would choose the lowest setting." Participant turns OFF bandwidth, as it covers temperatures above what he desires.

Task 4: You want to reduce your heating bill without compromising on comfort. What do you do?
Observations: *"This is what matters to me: how much am I saving with the settings I choose?"* Decides on 17° with ±1°, *"I'm not sure I would like this, I hope this wouldn't be necessary for too long."*

Post-Test Survey (Qualitative Questions)
How did you decide on your bandwidth settings?
Response: *"I played around with the buttons to visually see what I'm comfortable with, and set the temperature to what I have at home. The bandwidth could save me money, and I don't think I would notice 1° of difference really."*

Did you feel in control over your heating? Why or why not?
Response: *"Sure, yeah, I press the buttons and the system reads what I want. I would like some more information or feedback, but I do feel in control."*

What was not clear about bandwidth heating adjustments?
Response: *"The insights, what I mentioned before."*

Would you trust this system to optimize heating for you? Why or why not?
Response: "*To a point yes, I'd check in in the beginning to see what it is really doing.*"

Was there a moment where you felt confused? What caused it?
Response: "*No, not really confused just more, unsure I'd say.*"

Would you be open to using such a system in your life? Why or why not?
Response: "*Yes, if I have some control and it saves me money I don't see why not*"

Post-Test Survey (Quantitative Questions, Rate from 1-10, where 1 = Strongly Disagree, 10 = Strongly Agree)

The system is intuitive: 8
The system avatar is intuitive: 6 "*I didn't really pay attention to it*"
I feel confident using this system and understand how it works: 7
I agree with bandwidth heating hovering around my desired temperature if I save money: 9
I trust this system to not require my intervention: 6 "*I just want to know more about it first*"

Additional Notes: Participant never seemed to grasp the effect of bandwidth, skipped over menus for more information. Only focused on the dials. Stressed wanting feedback and suggestions for the actions. Sees value in bandwidth but wants more clarity on impact. Not necessarily looking for fully automation, but rather to grant the system space within which it can automate (which is what bandwidth is right now so that is nice).

Information Participant 9

Age: **31**
Tech Proficiency (Low/Medium/High): **Medium**

Pre-Test Exploration (1 minute)
Prompt: "Take a minute to explore the system. What do you think this system does?"
Response: "*Okay it is a heating system, a type of thermostat. It lets me adjust temperatures, and also temperature ranges. I see it is called a bandwidth. Because of the cost graph I assume it optimizes costs. The information window tells me bigger bandwidths are better. So I'd say it is a heat management optimisation-type system*"

Task-Based Interaction
Task 1: You just moved into a new home with this heating system. Set up the system to your preference, considering all parameters.
Observations: "*I want it to not be wasteful. Because of the bandwidth I feel like I want a higher temperature, because it can reach below my target.*" Finally decides on 19°, ±1°. "*On the other hand, 1° is so little. I think maybe I won't notice it too much. Do you know more about this, whether it is comfortable?*"

Task 2: Generally, you like the temperature of your home, but tonight you feel just a bit too cold. What do you do?
Observations: Reaches for temperature dial, but hesitates to click. "*Does this override settings or nudge it? Do I control what it is doing or just suggest what I want?*" After looking at a notification for a cost implication of adjusting temperature, "*I'd leave it as is. It can only be as cold as 18° so I don't think I would need anything.*"

Task 3: You are going on a vacation for one month. What do you instruct your heating system to do in this time?
Observations: "*Turn it off of course.*" Sets temperature to 10° with a wide bandwidth, "*This means it is as cheap as possible at 10° right?*"

Task 4: You want to reduce your heating bill without compromising on comfort. What do you do?
Observations: Experiments with a wider bandwidth, but is hesitant, "*This large bandwidth doesn't feel comfortable, I think*" Readjusts to ±1°. "*It depends on whether I'm home or not too. But if I have to choose one, I think I could go 1° lower.*"

Post-Test Survey (Qualitative Questions)
How did you decide on your bandwidth settings?
Response: "*I wanted to save money, but attain my comfort. I don't require very high temperatures but 17° feels too far off from 19°.*"

Did you feel in control over your heating? Why or why not?
Response: "*Mostly yes, it is easy to adjust by clicking. I like that the dial changes with*

the bandwidth to show me what it does. I'm not entirely sure of the effect of it, both in terms of comfort and cost"

What was not clear about bandwidth heating adjustments?
Response: *"I understand bandwidth is cheaper, but what will I notice of it? I see that the bunny becomes alerted when I increase the temperature."*

Would you trust this system to optimize heating for you? Why or why not?
Response: *"In this moment not really, I'd like some more explanation. Trust is not there yet."*

Was there a moment where you felt confused? What caused it?
Response: *"Yes, what I mentioned about the bandwidth. Just exactly what I can expect when I choose it."*

Would you be open to using such a system in your life? Why or why not?
Response: *"If the proposal is easy cost-saving; absolutely yes. I hope the interface improves to instill in me a greater sense of trust and understanding. But paying less for your heating at only a small impact in comfort seems to me like a no brainer?"*

Post-Test Survey (Quantitative Questions, Rate from 1-10, where 1 = Strongly Disagree, 10 = Strongly Agree)

The system is intuitive: 6
The system avatar is intuitive: 6
I feel confident using this system and understand how it works: 5
I agree with bandwidth heating hovering around my desired temperature if I save money: 9
I trust this system to not require my intervention: 7 *"I don't know, maybe?"*

Additional Notes: Sense of unsure behavior about bandwidth. Loves the concept of just saving money but is hesitant because they are not sure what their clicks grant them. Cautious. Prefers a bit more guidance interface-wise. Seems more inclined to gradual adoption rather than full trust.

Information Participant 10

Age: **58**
Tech Proficiency (Low/Medium/High): **Low**

Pre-Test Exploration (1 minute)
Prompt: "Take a minute to explore the system. What do you think this system does?"
Response: *"It is for heating, I think. I like the bunny image. What does 'unfavourable price window' mean? I don't understand entirely why my temperature is in a range."*

Task-Based Interaction
Task 1: You just moved into a new home with this heating system. Set up the system to your preference, considering all parameters.
Observations: Sets heating to 18°, misinterprets however what bandwidth means and as a result sets the 18° to the edge of bandwidth, thinking that they desire at least 18°, and bandwidth works only above their target temperature. Bandwidth stays on ±1°.

Task 2: Generally, you like the temperature of your home, but tonight you feel just a bit too cold. What do you do?
Observations: Only looks for manual temperature adjustments. Increases the temperature by 1°. *"Am I messing up the system now?"*

Task 3: You are going on a vacation for one month. What do you instruct your heating system to do in this time?
Observations: *"I would turn it low, but should I do so now too?"* Hesitates, but finally decides on doing what she regularly does and significantly lowers temperature.

Task 4: You want to reduce your heating bill without compromising on comfort. What do you do?
Observations: *"This feels like a trick question, I think this is maybe where the bandwidth could help me."* Adjusts bandwidth larger. *"What does this mean now I select it?"*

Post-Test Survey (Qualitative Questions)
How did you decide on your bandwidth settings?
Response: *"I just set the temperature to what I like, and the bandwidth on medium. I'm not sure what to do so I thought medium is always okay."*

Did you feel in control over your heating? Why or why not?
Response: *"Yes but I didn't feel like I knew too much about what I was doing."*

What was not clear about bandwidth heating adjustments?
Response: *"I am uncertain about its effects. But if you say it saves money it is good."*

Would you trust this system to optimize heating for you? Why or why not?
Response: *"Maybe, I trust you that it is a product that does it. But I don't feel comfortable with it yet"*

Was there a moment where you felt confused? What caused it?
Response: "*Immediately, I am just not used to these types of products. I'd probably look up an explanation or video of someone using the system.*"

Would you be open to using such a system in your life? Why or why not?
Response: "*Yes, I see the value. But I like to discover things in my own way and would take some time to understand it better. The interface was not enough information for me. I would probably order this and on the packaging see information about what it is I am buying.*"

Post-Test Survey (Quantitative Questions, Rate from 1-10, where 1 = Strongly Disagree, 10 = Strongly Agree)

The system is intuitive: 3
The system avatar is intuitive: 5 "*Oh, I didn't link it to system status. Now you say that I understand better that it tells me about what the consequences are*"
I feel confident using this system and understand how it works: 5
I agree with bandwidth heating hovering around my desired temperature if I save money: 9 "*I can agree with the idea fully! Saving money is always nice*"
I trust this system to not require my intervention: 6 "*Trust would come over longer time and familiarity.*"

Additional Notes: Somewhat frustrated about the additional options, lost in hesitation. Really likes the idea of bandwidth heating and saving money, but can't really grasp the interface.

Appendix K: Original Project Brief

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Berend Andre de Bont **Student number** 4683064

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Designing for household contribution to balanced utilisation of heat-pump fed district heating systems.

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Heating is one of the main energy consumption areas in Europe, making it a critical area for innovation and efficiency improvements. In this context, the project focuses on the domain of district heating networks, particularly on a concept from Alliander that utilises a heat pump as a supply. This heat-pump fed district heating (HPDH) networks offer carbon-savings through providing energy efficienct centralized heating to homes. A first concept has been realised in Didam, a second concept is now being developed for implementation in Loppersum. I aim to contribute to the success of the second concept through this graduation project.

The main stakeholders in this domain include Alliander (DEP) and end-users. Alliander operates, maintains and develops the heating network and is in the unique position of being able to provide electricity as a utility company. End-users are facing the adoption of DH, their use-patterns and embrace influences the efficiency and economical operation of a HPDH system. Tertiary stakeholders may include environmental groups, policymakers, homeowners' assocititations and contractors.

Interests at stake are sustainable innovation, carbon reduction, energy supply security and heat balancing. The project aims to investigate how collaborative efficient use can be encouraged in households, while designing for the system to achieve/foster this outcome. The goal of this project is to improve HPDH efficiency, allow for a larger connection density without source scaling and lowering the costs of both install and operations.

Limitations are technical challenges, financial barriers and utility company trust erosion. Consumer acceptance and behavior change may impact the widespread adoption of HP-fed DH system.

Through research and exploration, this project seeks to design on the intersection of system and user for optimal results.

➔ *space available for images / figures on next page*

introduction (continued): space for images

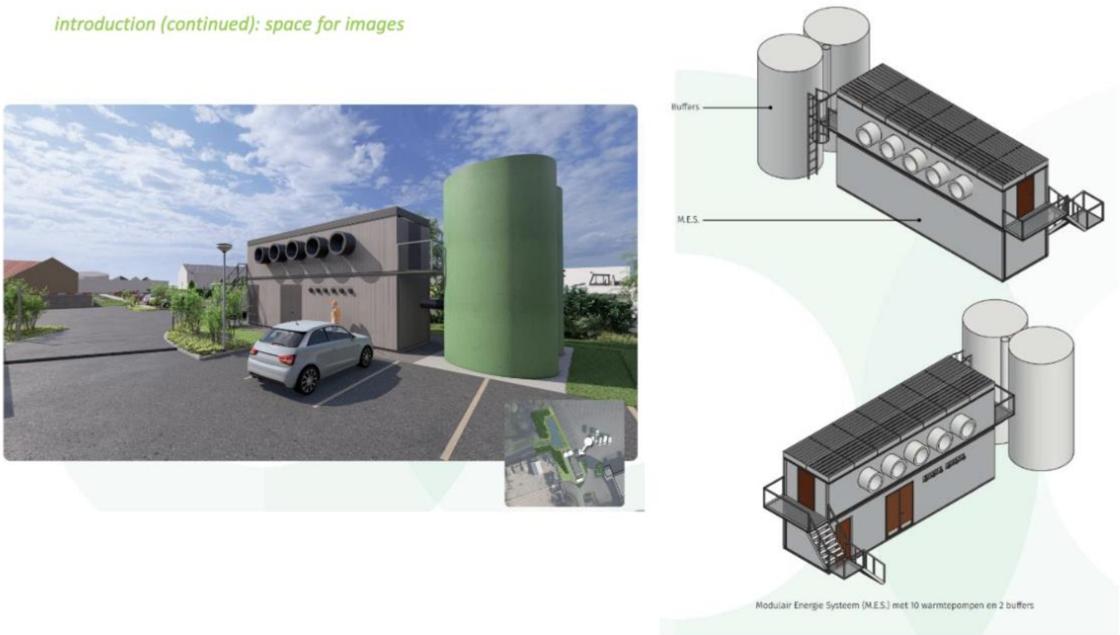


image / figure 1: Expected heat pump characteristics of second prototype implementation in Loppersum

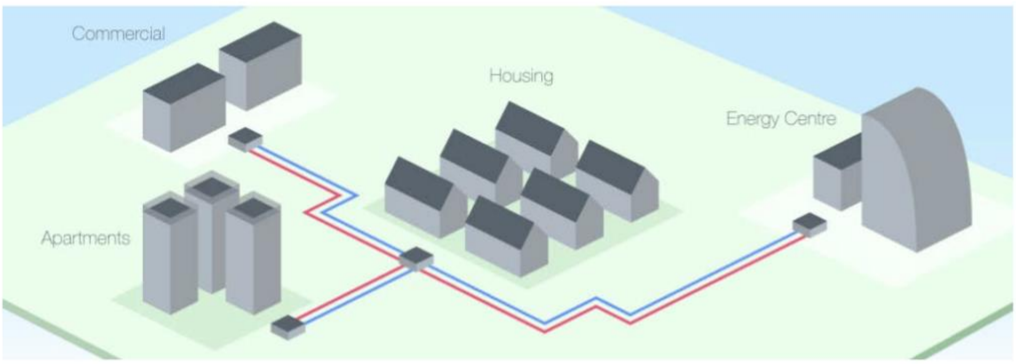


image / figure 2: Simplified district heating network. This project focus is on residential heating, the energy center is a heat pump.

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

The project adresses the sustainable transition of the heating market through successful implementation of HPDH. The main objective is to realise balanced heating amongst users, where peak demand is prevented through better use of the system.
Potential benefits per party.
Alliander: Increase acceptance of HPDH, balanced heating utilisation, sustainable heating, local grid relief
User: Decrease costs through lowering energy cost, sustainable heating

1. Balanced heating: Successful stakeholder integration will lead to optimisation of energy usage and teach consumers how to use HPDH. This allows for more balanced heating and efficient use of available resources, through e.g. preventing peak demands.
2. Decrease costs: Both on the install side (maximizing connection density without source scaling), and the operation side (efficient behavior adds to higher density of connections in turn lowering costs, while efficient use also decreases direct consumption costs).
3. System Resilience: Realising balanced use can contribute to reliable provision of heating.
I want to add value by developing an integrated product on the intersection of end-users and the system to ensure

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design and validate a product-service-system that optimises collaborative balanced consumption in heat-pump fed district heating systems.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

The research portion entails better understanding of the current state of (HP)DH, investigating expected future trends, identifying where complexities lie as well as researching household heating behavior through surveys. This approach equips me to decide on design opportunities. Systemic design tracks of both the technical and product/user perspective will aid. Customer research can provide insights into potential customers, experiences of customers or doubts with new customers.

The rest of the project focusses on effective design that enables two sides of the story. Equipping Alliander with the knowledge of household behaviors and optimising for lower install costs and higher connection density. Households are nudged to efficient use in turn decreasing heating costs and restoring trust in utility companies, as well as broader advantages of sustainable practice.

This way, the design solution can capture value for stakeholders on varying facets of good design: sustainable, economical and transparent heating.