DESIGN OF A HEAT RECOVERY SYSTEM FOR IN THE KITCHEN CONTEXT

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GLOSSARY

Greywater: domestic wastewater generated in households e.g. by the shower, dishwasher and sink except toilet wastewater. This water includes e.g. dirt and fats.

Blackwater: wastewater that contains human waste, typically originating from toilets.

HEX: Heat Exchanger

TEG: Thermo Electric Generator

ABSTRACT

This project aims to create a proof of concept to evaluate the potential value of implementing a heat recovery system for Quooker in the kitchen context. In response to the global goal of achieving net-zero CO_2 emissions by 2050, reducing energy loss has become a shared priority. Heat recovery systems can significantly decrease energy consumption, leading to economic and sustainable benefits. In collaboration with Quooker B.V., this project assesses the feasibility and impact of integrating such a system in kitchen environments.

The evaluation follows a triple diamond approach, consisting of four stages: discover, define, develop, and deliver. During the discover phase, extensive research is conducted on kitchen contexts, user behavior, existing heat recovery systems, and the characteristics of current kitchen setups. The define phase involves exploring various design directions, identifying potential hazards, and selecting a single promising direction for further development.

In the development phase, two design principles are prototyped and tested to determine which one offers the optimal heat recovery rate relative to its initial cost and carbon footprint. The deliver phase focuses on final testing, where the developed concept is evaluated for efficiency during typical kitchen activities, such as draining water after cooking and using the dishwasher. The results are analyzed over a 10-year period of daily use.

The project concludes with an assessment of the final concept's viability, feasibility, and desirability.
Recommendations for further research and potential hazards associated with the implementation of the heat recovery system for Quooker are provided.

TABLE OF CONTENTS

DISCOVER
DEFINE
DEVELOP
DELIVER

01

INTRODUCTION

In 2021, the International Energy Agency (IEA) highlights that approximately three-quarters of today's greenhouse gas emissions originate from the energy sector (IEA, 2021). Therefore, there is a pressing need for a significant shift in energy supply and conversion to achieve global net-zero CO2 emissions by 2050. Consequently, addressing this issue is a shared responsibility that extends to governments, municipalities, companies, and individuals, each with their own stake in the matter.

According to Tohidi et al. (2022), energy demand is predicted to increase. An opportunity to improve energy efficiency involves exploring heat recovery systems in households. Currently, existing solutions for wastewater in households, such as showers, are mainly focused on the bathroom context. However, there is a lack of solutions tailored to the kitchen context.

1.1. ASSIGNMENT

In light of the global initiative to achieve net-zero CO2 emissions by 2050, energy efficiency and the prevention of energy loss are becoming more important (Sorrell, 2015). This goal is a collective responsibility for governments, municipalities, corporations, and individuals. Implementing heat recovery systems could be a potential solution to work towards this shared goal. Heat recovery systems reduce energy consumption, resulting in sustainable and economic value (Selimli et al., 2019). Recognising the potential impact, Quooker aims to investigate the feasibility of harnessing residual heat from water for integration into their boiling water Quooker system.

For the evaluation of the viability of heat recovery for Quooker, an exploration of diverse heat recovery systems is desired with merits and drawbacks. Furthermore, conducting an analysis, which involves the development of a functional prototype, of the most promising system can help to evaluate the sustainable and economic value of such a system. This investigation supports Quooker's goals of innovation, sustainability efforts, and brand positioning and aligns with the shared goal of achieving net-zero CO2 emissions by 2050.

Next to making a heat recovery system feasible for the kitchen context (tap, cabinet, sink or drain), it is important to investigate whether such a system is economically and sustainably profitable as well for Quooker as for the end user. This project focuses on users in the Netherlands as a starting point, and therefore the assignment is:

Create a Proof of concept to evaluate the value of implementing a heat recovery system in the kitchen context in the Netherlands.

1.2. COMPANY

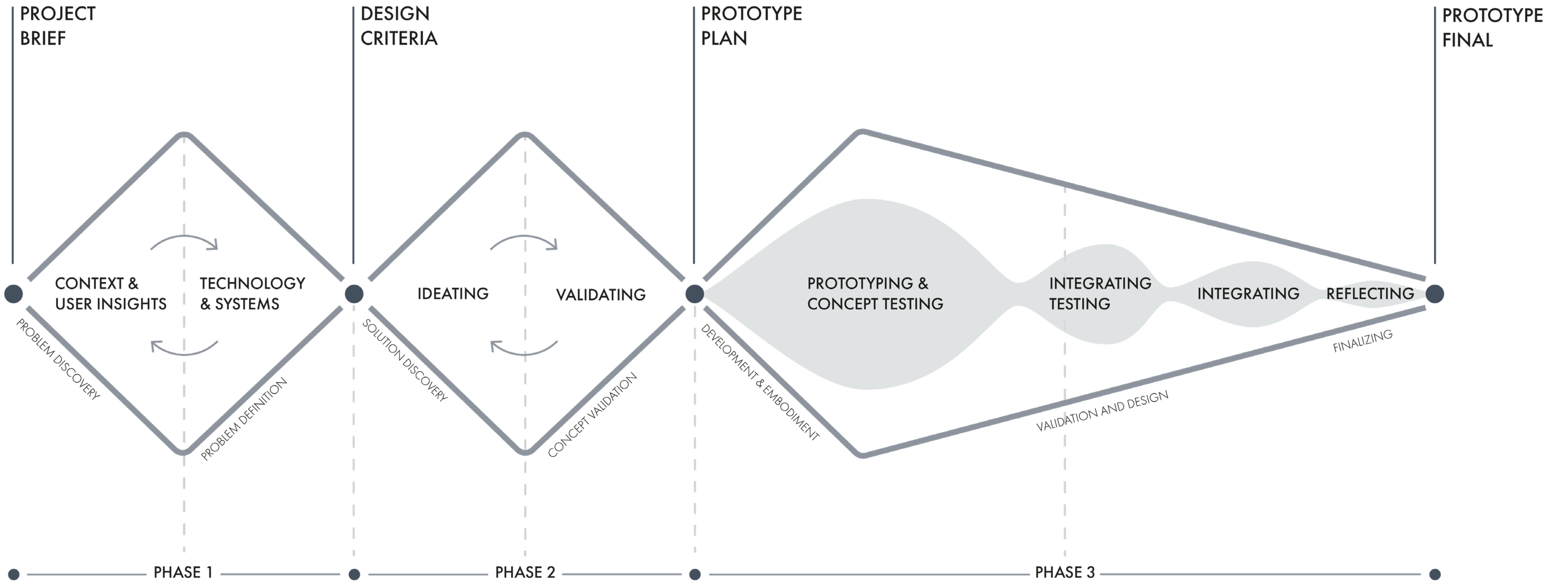
Quooker, a Dutch company, is interested in a heat recovery solution for warm wastewater in the kitchen. The company specializes in mixing taps, instant boiling and sparkling water dispensers and accessories such as soap dispensers or water filters. Quooker is growing rapidly: they are now mainly active in Europe and are quickly expanding to other continents (Quooker, n.d.). Even though they currently (2023) produce 300.000 Quooker systems a year, all their products are assembled in-house, in the Netherlands (Quooker, n.d.). Quooker systems are high-end products and therefore Quooker mainly targets wealthy homeowners.

1.3. STRUCTURE & PLANNING

For this projects approach, a triple diamond model is implemented, dividing the project into three phases (Figure 1):

Phase 1 involved identifying the problem across different domains. Research was conducted on the available energy within the kitchen context, with an examination of user behavior and the technological and systemic aspects of heat recovery. These efforts aimed to comprehensively define the problem. Phase 2 was mainly building on the discovery phase of the first phase. Herein a design direction and prototype plan were formulated. In phase 3, the final phase of the triple diamond model was more time-intensive, as it not only elaborated on the development of a prototype to demonstrate proof of principle but also the delivery of the final concept. This included conducting valuable tests and evaluating the desirability, feasibility, and viability of the final concept.

During the project, biweekly meetings were organised with the supervisory team of Delft University of Technology, and weekly meetings were organised with the company mentor. In addition, frequent project updates were given to other important stakeholders within the company through presentations and through interviews and conversations.



(Figure 1: project planning approach)

DISCOVER

02

AVAILABLE ENERGY

A regular kitchen consists of different appliances or systems for cooling and heating purposes. Most of these appliances or systems use energy from the domestic energy net and some produce rest warmth either in liquid form or gas form. In this Chapter, the available energy in the rest warmth of warm grey water in the kitchen context is investigated.

KEY INSIGHTS

- Warm grey water coming from the dishwasher and sink should be combined in a heat recovery system to reach its fullest potential.
- -The higher the temperature difference between the warm and cold water inlet in a heat recovery system, the higher the possible heat recovery efficiency rate.
- Experimental studies show that attaching a heat recovery system to a dishwasher can have an efficiency rate of 22.3% on the eco programme and 29.8% on the high-intensity programme.

2.1. MAXIMUM VALUE

In the kitchen there are generally two sources of warm grey water: the kitchen sink and the dishwasher. To get a better understanding of the energy that can potentially be recovered from warm grey water, in this paragraph, an estimation of the available amount of energy in warm wastewater in the kitchen is made.

According to Statista (2023), the household ownership of dishwashers rate in the Netherlands is estimated at 68 percent. Since this is the majority of the households, the estimation of the available amount of energy in warm wastewater is based on a household that uses a dishwasher for the main dishes. Additionally, this estimation is based on a household that owns a Quooker kettle and thus has access to direct boiling water. This estimation does not include additional warm water use in the kitchen sink e.g. washing pans (Chapter 3.4).

"In essence, it is possible to recover nearly 100 percent of the energy from your warm greywater. Some energy loss to the surroundings is inevitable, but this can be accounted for in the design of a heat recovery system." - professor in Mechanical Engineering at Delft University of Technology, 2023

SINK

For the estimation of the available energy that is drained through the sink by a household that owns a Quooker kettle, the following assumptions were made:

Figure 2 shows the estimated available energy, cost and carbon footprint after 10 years of use (Appendix A1). The available energy cost in this scenario is based on the average price of one kWh in December 2023, which was €0.38 per kWh (Tess, 2023). For the calculation of the Carbon Footprint, 502gCO2eq/kWh was used. This was the average emission in December 2023 (Nowtricity, 2023).

ASSUMPTIONS

1. A Dutch household uses 1.5L of boiling water from the Quooker kettle a day for cooking purposes and drains this 1.5L boiling water through the kitchen sink.

2. The temperature of the boiling water drained in the kitchen sink is 80 °C once it reaches the drain system under the kitchen sink.

3. he lifespan of a potential heat recovery ystem is 10 years.

kWh sink	Cost sink	CO2 sink
445 kWh	€ 169	228 kg

(Figure 2: total available energy, cost and carbon footprint after 10 years use in the sink)

DISHWASHER

For the estimation of the available energy that is used by a dishwasher, the following assumptions were made:

ASSUMPTIONS

1. A dishwasher is used one time a day, based on the use of a family with children (Bakker et al., 2022).

2. A dishwasher has four cycles. Each cycle uses approximately 4.5 L of water (figure 3).

3. The lifespan of a dishwasher is 10 years.

STEPS (4.5L refill each)	**LOW** (eco)	**HIGH** (intense)
1. Prewashing	19 °C	45 °C
2. Main washing	41 °C	58 °C
3. First rinsing	32 °C	47 °C
4. Second rinsing	45 °C	64 °C

(Figure 3: water temperature in the dishwasher at each cycle on eco (low) and intense (high) programme)

To be able to compare the calculation of the available energy of the sink with the dishwasher, the same values for the price and carbon footprint of one kWh were used as named earlier in this paragraph. Additionally, the lifespan of the dishwasher was assumed the same as the lifespan of a potential heat recovery system. The temperature of the water of each cycle is shown in Figure 3 (Selimli et al., 2019).

kWh eco	Cost eco	CO2 eco
1850 kWh	€ 703	949 kg

(Figure 4: total available energy, cost and carbon footprint of the dishwasher (DW) on eco programme after 10 years of use)

kWh intense	Cost intense	CO2 intense
3318 kWh	€ 1261	1702 kg

(Figure 5: total available energy, cost and carbon footprint of the dishwasher (DW) on the high-intensity programme after 10 years of use)

Figures 4 & 5 show the estimated available energy, cost and carbon footprint after 10 years of use of the dishwasher both on eco and high-intensity programmes (Appendix A1). Since the cost and carbon footprint are directly related to the available energy in kWh, the cost and carbon footprint rise as the available energy rises. Figures 4 and 5 show that the use of the dishwasher on the high-intensity programme results in nearly the double amount of available energy in the eco programme. Thus, the cost and carbon footprint are also nearly doubled on the high-intensity programme.

2.2. COMBINATION IS KEY

In the previous paragraph, the available energy, cost and carbon footprint of the use of the sink and dishwasher were discussed. The sink scenario uses less water but consists of a higher temperature. The dishwasher uses more water but with lower temperatures.

A comparison of the available energy between the use scenario of the sink and dishwasher shows that the eco programme of the dishwasher contains more than 4 times the available energy than the sink use scenario. For the high-intensity programme, this number is even higher: approximately 7.5 times more available energy than the sink use scenario.

For a higher chance to create a system that recovers heat from warm grey water in the kitchen, it is beneficial to combine the warm grey water coming from the sink with the warm grey water from the dishwasher into one heat recovery system. Figure 6a-c shows the sum of dishwasher use and sink use in terms of kWh, cost and carbon footprint.

kWh sink + eco = 2295 kWh	**kWh sink + intense = 3365 kWh**

Figure 6a: available energy

Cost sink + eco = € 872	**Cost sink + intense = € 1430**

Figure 6b: cost

CO2 sink + eco = 1177 kg	**CO2 sink + eco = 1930 kg**

Figure 6c: carbon footprint

Figure 6a-c: sum of dishwasher (DW) and sink use for total available energy, cost and carbon footprint over 10 years of use)

2.3. PROVEN EFFICIENCY

An experimental study of the efficiency of a heat recovery system attached to a dishwasher that was conducted by Selimli et al. (2019) proves that attaching a heat recovery system to a dishwasher can have an efficiency rate of 22.3 percent on the eco programme and 29.8 percent on high-intensity programme.

A reduction rate comparison between the eco and high-intensity programme highlight that higher temperature differences result in a higher heat recovery rate. Therefore, the reduction rate of the sink scenario (with higher greywater temperature) from paragraph 2.1 is expected to reach higher heat recovery rates.

To get a closer evidence-based estimation of the potential of applying a heat recovery system, the proven reduction percentages mentioned earlier are applied to the sum of eco or high-intensity programme and sink use of figure XX (figure 7a-c).

kWh sink + eco = 511 kWh	**kWh sink + intense = 1122 kWh**

Figure 7a: energy reduction

Cost sink + eco = € 194	**Cost sink + intense = € 426**

Figure 7b: cost reduction

CO2 sink + eco = 262 kg	**CO2 sink + eco = 575 kg**

Figure 7c: carbon footprint reduction

Figure 7a-c: sum of reduction dishwasher (DW) and reduction sink use for total available energy, cost and carbon footprint over 10 years of use)

DISCOVER

03

CONTEXT

This project focuses on heat recovery of warm/hot grey water in the kitchen context. In this Chapter, the kitchen context is discussed. Information about the context is gathered through Interviews with users and experts, observations, desk research, and user tests. Several topics are elaborated on, such as the kitchen composition, the user behavior around the dishwasher and sink, and the water behavior in the current context.

KEY INSIGHTS

- Kitchen cabinet space is limited.
- Common practice places the dishwasher near the sink for efficiency. The drain system of both is often connected.
- Users prioritize cost, but are willing to pay more if they strongly desire the product.
- Factors that influence purchasing are: initial cost, return on investment, quality, durability, aesthetics, functionality, sustainability, size, noise, installation, user-friendliness, and repairability.
- For some customers, energy-recovering product should not only be net sustainable but should also have a return on investment.
- Use behaviour around the kitchen sink and dishwasher (in terms of amount and temperature of water) differs much from user to user and per day/use scenario.
- Pans are washed in the kitchen sink even though a user owns a dishwasher. Plates are often also first rinsed in the kitchen sink.
- Water that is drained through the dishwasher- and kitchen sink drain is dirty and contains e.g. oils, fats, (food) particles, soaps or other cleaning substances, but also drinking water substances that may have other drawbacks for a HEX system.
- Cold grey water or grey water that has a lower temperature than the clean water in the buffer system should be diverted directly to the drain so that it will not go through the HEX system. Therefore the system must be able to measure the temperature of incoming grey water and the clean water in the buffer system.
- The water flow in the system behaves not completely laminar or turbulent.

3.1. KITCHEN

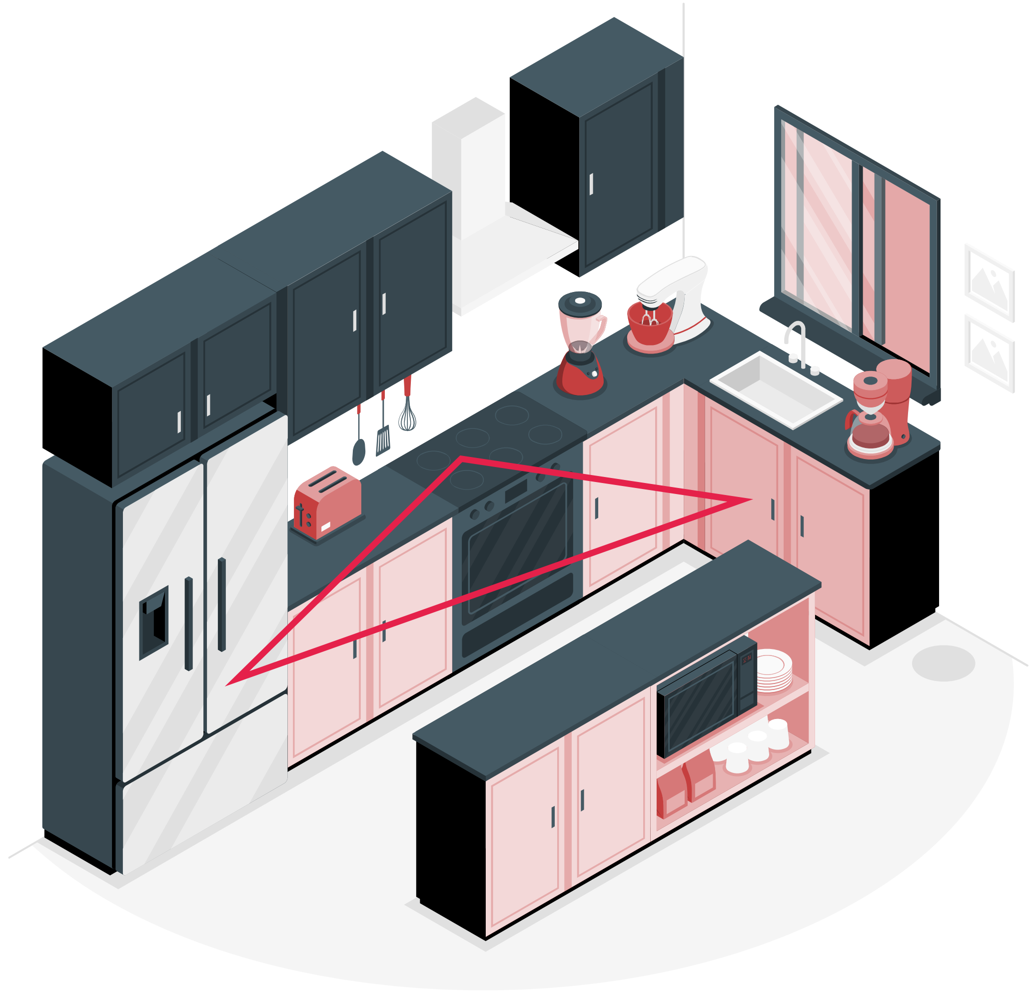
Kitchens are available in all shapes and sizes. Additionally, kitchens can have multiple different compositions. Still, there are relations between certain compositions and user preferences. In this Chapter, different work zones, the kitchen triangle, and the dishwasher and sink connection are discussed.

IDEAL KITCHEN COMPOSITION

Generally, kitchens have different work zones. The work zones are regarded as distinct components within the kitchen (Keukenontwerp, 2021):

1. Cleaning zone: processing dirty dishes.
2. Preparation zone: where you cut and prepare your food, where you wash your vegetables.
3. Cooking zone: where your stove is located.
4. Cooling zone: storing food in a cool, dry, and freezing environment. The main component is the refrigerator.
5. Storage zone: storing appliances.

When a kitchen is designed, often the ideal kitchen triangle is taken into account (Britt, 2023). The ideal kitchen triangle consists of an optimal configuration of the kitchen workspace comprising three integral elements: the stove, refrigerator, and sink also referred to as the cooking, cooling, and cleaning zone (Figure 8).



(Figure 8: kitchen triangle)

IDEAL KITCHEN COMPOSITION

Common practice situates the dishwasher in immediate proximity to the sink, to create a seamless transition of rinsed items into the appliance (Scheffer Keukens, n.d.). This arrangement, influenced by considerations of task efficiency, suggests rerouting the piping so that the dishwasher does not obstruct the flow during the further use of the work zones in the kitchen (Keukenontwerp, 2021). Figure 9 shows an example of the connection between the dishwasher and sink drain.

(Figure 9: Connection of the kitchen sink drain and dishwasher drain)

3.2. CABINET STORAGE

Quooker sells different Quooker systems and products. In this paragraph, kitchen sink cabinet dimensions and the Quooker systems that are commonly installed in the kitchen sink cabinet and that may influence a heat recovery system design are discussed.

CABINET

According to Itereno (2022), commonly used sizes for the kitchen sink is 450 x 450 mm and 500 x 500 mm.
IKEA shows to have most models of kitchen sink cabinets available in approximately the following dimensions (IKEA, n.d.):

Width = 600 mm
Depth = 600 mm
Height = 800 mm

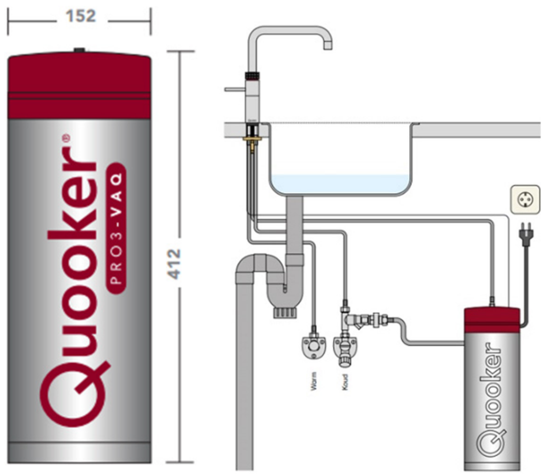
QUOOKER PRODUCTS

A kitchen with all Qyooker systems can serve water in 5 variations: boiling, warm, cold, sparkling and chilled water (Figure 9).

(Figure 9: different Quooker systems)

PRO3

The PRO3 internally brings water to a temperature of 108 °C. The maximum amount of boiling water in this tank is 3 liters. Once this boiling water is requested out of the tap, the water leaves the tap with a temperature of around 100 °C. In currently available systems, the pressure in this system is controlled through a bellows system and is connected to the cold water supply. Older systems have an additional pressure valve to control the internal pressure of the tank. The PRO 3 is only suitable for users that have both a cold water and warm water connection in their kitchen. The PRO3 cannot provide warm water, only boiling water. Figure 10 shows the dimensions of the Quooker PRO3 system and its connection to the cold water supply.

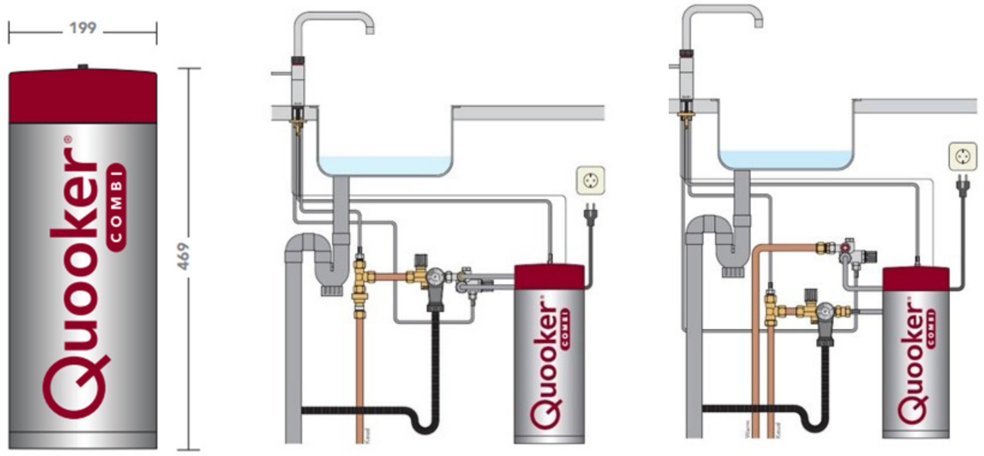


(Figure 10: dimensions in mm of Quooker PRO3 and connection to water supply (Quooker, n.d.))

COMBI & COMBI+

The COMBI and COMBI+ systems serve the same purpose and have in essence the same working principle as the PRO3 kettle. However, the maximum amount of boiling water these tanks produce is 7 liters instead of 3 liters of the PRO3.

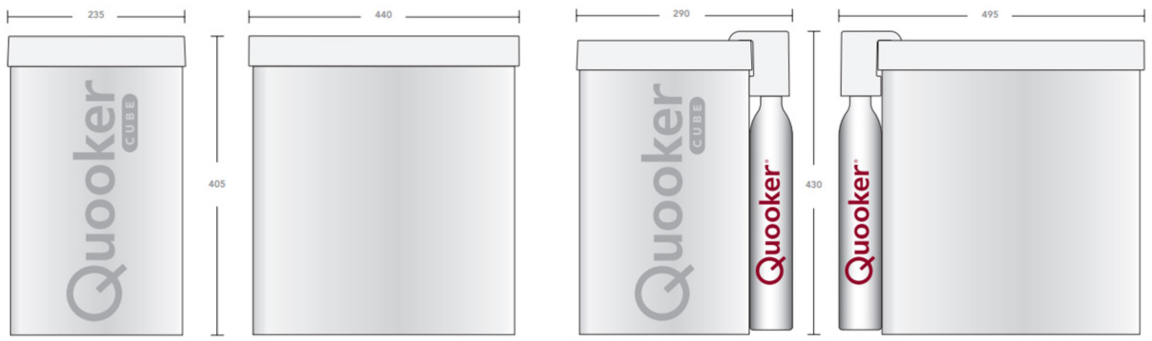
Other than the difference in boiling water capacity, the COMBI and the COMBI+ can produce next to boiling water also warm water through a mixing valve. The difference between the COMBI and COMBI+ systems is that the COMBI system can only provide 15 liters of warm water at once, whilst the COMBI+ provides unlimited access to warm water. This is a result of the COMBI system that works with only a cold water supply and the COMBI+ works with both a cold and warm water supply connection (Figure 11). These systems ensure that there is no waiting time for warm water when warm water is requested by the user.



(Figure 11: dimensions in mm of Quooker COMBI(+) (left) COMBI water connection (middle) COMBI+ water connection (right) (Quooker, n.d.))

CUBE

The CUBE is sold as an add-on to the Quooker kettle and is made to provide chilled and/or sparkling water. This system can provide 60 litres of chilled sparkling water. The CO2 bottles for sparkling water can be replaced manually. This bottle can be placed either on the side of the CUBE or on the back of the CUBE



(Figure 12: dimensions in mm of Quooker CUBE (left) & with CO2 cylinder attached to side (middle) and to back (right) (Quooker, n.d.))

STORAGE

As mentioned earlier, different Quooker systems are supposed to fit in the kitchen cabinet. Figure 13 shows different kitchen cabinets with different configurations. These pictures were taken at the beginning of this project during a walk along with a Quooker Service Engineer to repair and maintain Quooker systems at users' homes. The Figure shows that there is a significant difference in leftover space between different households in the kitchen cabinet. This difference is created by sthe different sizes of the cabinets, the configurations of the drain pipes, the placement of the Quooker systems (in or behind the cabinet), and the amount of different Quooker systems. Interviews with users showed that the kitchen cabinet is not only used to store Quooker systems but also for other storage items like cleaning- and kitchen equipment and trashcans. Therefore, the additional storage space for a heat recovery system is limited.

(Figure 13: different compositions of Quooker systems in kitchen cabinets under sink during an observation day with a service technician)

3.3. USER DESIRES

To get a better understanding of the users' needs and desires for energy-recovering products, exploratory research was conducted through four qualitative interviews (Appendix A2).

To get a better understanding of the users' needs and desires for energy-recovering products, exploratory research was conducted through four qualitative interviews (Appendix A2).

During the interviews, all interviewees mentioned that they believe they make sustainable choices and all own energy-saving products like solar panels, a heat pump or a well-energy-labeled house. All participants were interested in buying new energy-saving products in the future.
The interviews showed that the following aspects are taken into account when they would consider buying an energy-recovering product:

- Initial cost
- Return of investment
- Quality & durability
- Appearance/aesthetics
- Functionality
- Net) sustainability
- Size
- Noise/disruption
- nstallation
- User-friendliness
- epairability

Interestingly, these interviews showed that costs or an economic benefit are often mentioned to be more important than that an energy-recovering product is net sustainable. However, in case the user finds enough benefits and thus enough desire to buy a product, the price is likely to have lower importance:

"If I really believe that a product if sustainable and durable and looks good, then I am willing to pay more for the product. However, the cost can be an immediate deal breaker in case I do not feel like I want the product that much. This desire for a product for me is created by the aesthetics of a product, net sustainability and the quality and durability of a product."

Additionally, the aesthetics, functionality, sustainability, and quality of a product are shown to be important factors for the user to be willing to pay more money. One of the interviewees stated that it was difficult to tell what an energy-recovering product in the kitchen could cost. Some interviewees mentioned that an important factor for buying new additions in the kitchen is that this consideration is often made when making renovations in the kitchen or changing to a new kitchen. Since making changes to a kitchen is already a big investment where people to save money, people are likely to be willing to make investments for their new kitchen to be exactly as they desire. One of the interviewees gave an example about choosing a more expensive option for a range hood so that it was integrated in the kitchen counter:

"I saw these products, found them aesthetically pleasing and functional with its extra benefits. I was immediately convinced, even though this product was almost double the price of a regular range hood. I have to say that once we chose to get the new kitchen, we were already paying a lot of money, so I wanted the kitchen to be exactly how I wanted it. Therefore paying more was at that moment not that much of a problem for an addition in my kitchen that I desired."

For the longevity or return of investment, the interviewees again mentioned that it was difficult to say what the timespan was allowed to be. They mentioned that there are different factors involved, such as initial cost, whether the product retains its value and e.g. whether it adds value to the house.

"I really cannot say. In case we are talking about the kitchen, I believe that if you buy such a product, I expect it to last as long as I live there. But still, it is difficult to say because it also depends on the initial cost. Another important factor is that something is value retaining. I look at the whole package, everything together."

In conclusion, an energy-recovering product should not only be net sustainable but should also have a return on investment. To determine what the initial cost and the return on investment time of an energy-recovering product are allowed to be, different aspects are at stake. Most important is that the user should feel the desire to own a product. As long as the desire is high enough, the price can be higher and the payback time can be longer too. The desire to buy a product can increase by incorporating factors like aesthetics, functionality, and net sustainability in the design of an energy-recovering product.

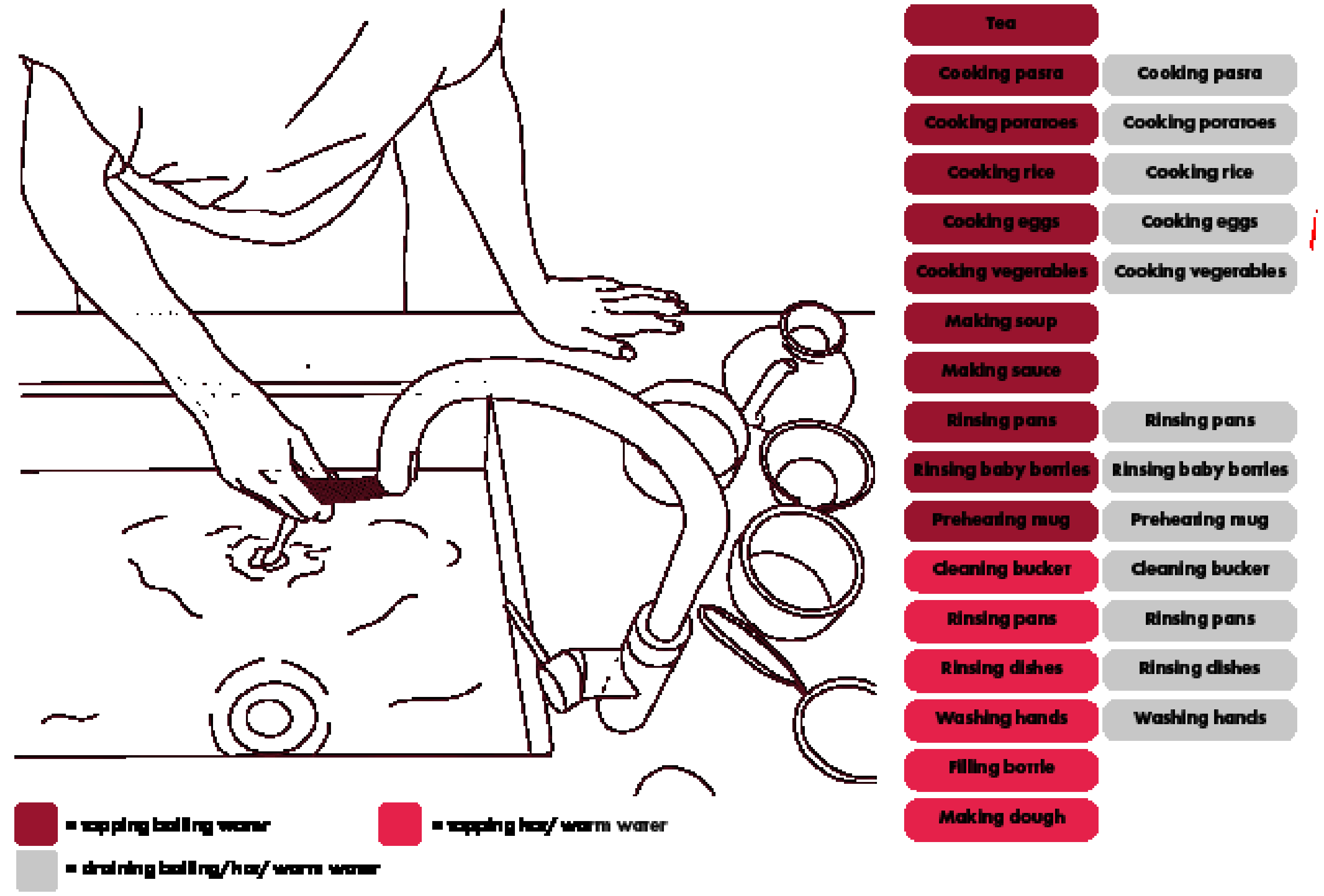
3.4. USE AND BEHAVIOR

In this paragraph, the use and behavior of the dishwasher and the kitchen sink are discussed. Through interviews, observations, desk research, and user tests, an overview is created of the user behavior on draining and tapping warm or hot water.

BEHAVIOR SINK

In an exploratory study about the behavior around the kitchen sink, Dutch participants were asked to name the moments they use the boiling water from their Quooker tap, when and why they tap warm/hot water from the tap, and the moments where they drain hot/warm water. Warm water was defined as water that did not feel cold, but was touchable by hand. Hot water is defined as water that is not touchable by hand. After these questions, some of the participants were observed at different moments of the day (morning, noon, and afternoon). Additionally, a user test where participants were asked to (time) track their behavior around tapping and draining hot/warm water on two weekdays and two weekend days, gives insight into the user behavior around the sink and the dishwasher (Appendix A3 & A4). Not all participants tracked four full days, some tracked their behavior for two days. This user test was conducted by a total of five (N=5) participants of which one had no dishwasher. All participants had a Quooker kettle at home.

According to Quooker (n.d.) and the outcomes of the exploratory about tapping and draining behavior, the following actions around the kitchen sink were found (figure 14):



(Figure 14: tapping and draining actions in the kitchen)

This list shows that most of the actions around the kitchen sink result in hot/warm water being tapped, but afterwards also drained. Only actions like making tea, soup, sauce, or dough result in only tapping behavior without draining the water after use.

Another interesting insight from the observations, interviews, and user tests is that the rinsing behavior of users can differ among different users. Contrary to popular belief, some users rinse their pans with boiling water.

One user mentioned that "using boiling water for rinsing pans makes rinsing faster than with hot or warm water" (Figure 15).

Additionally, it was interesting to see that some users would first fill their pan with hot water and stop the tap from running, then use soap and a dishwashing brush to do the first rinse and then empty the pan to quickly do a final rinse round whilst letting the tap run with water for the additional time needed to clean the pan (figure 16). Other users leave the tap running throughout the whole rinsing process and others fill their kitchen sink to do multiple dishes at the same time. Also, the water temperature used to do quick rinsing of plates or to rinse their pans differs from lukewarm water to hot water or boiling water. Users mentioned that their way of cleaning (the water temperature they use or the amount of water they use) would also be different each day. Therefore, it is difficult to say what the average temperature and amount of drained water are. An important note is that the rinsing behavior in the kitchen sink is not taken into account in the calculation of available energy in Chapter 2. The real available energy will therefore be higher than mentioned in Chapter 2.

(Figure 15: user rinses pan with boiling water)

The outcomes of the amount of warm/hot water drained through the kitchen sink in the exploratory user test were the following (Appendices A3 & A4):

Participant 1 (has no dishwasher):
- Week day 1 (4 friends over for dinner): 73.5 L
- Week day 2 (work at home, out for dinner): 4 L
- Weekend day 1: 60.5 L
- Weekend day 2: 48 L

Participant 2:
- Weekend day 1: 38.6 L
- Weekend day 2: 41.5 L

Participant 3:
- Week day 1: 6 L
- Week day 2 (did not cook): 1 L
- Weekend day 1 (went out for dinner): 9.75 L
- Weekend day 2: 10.5 L

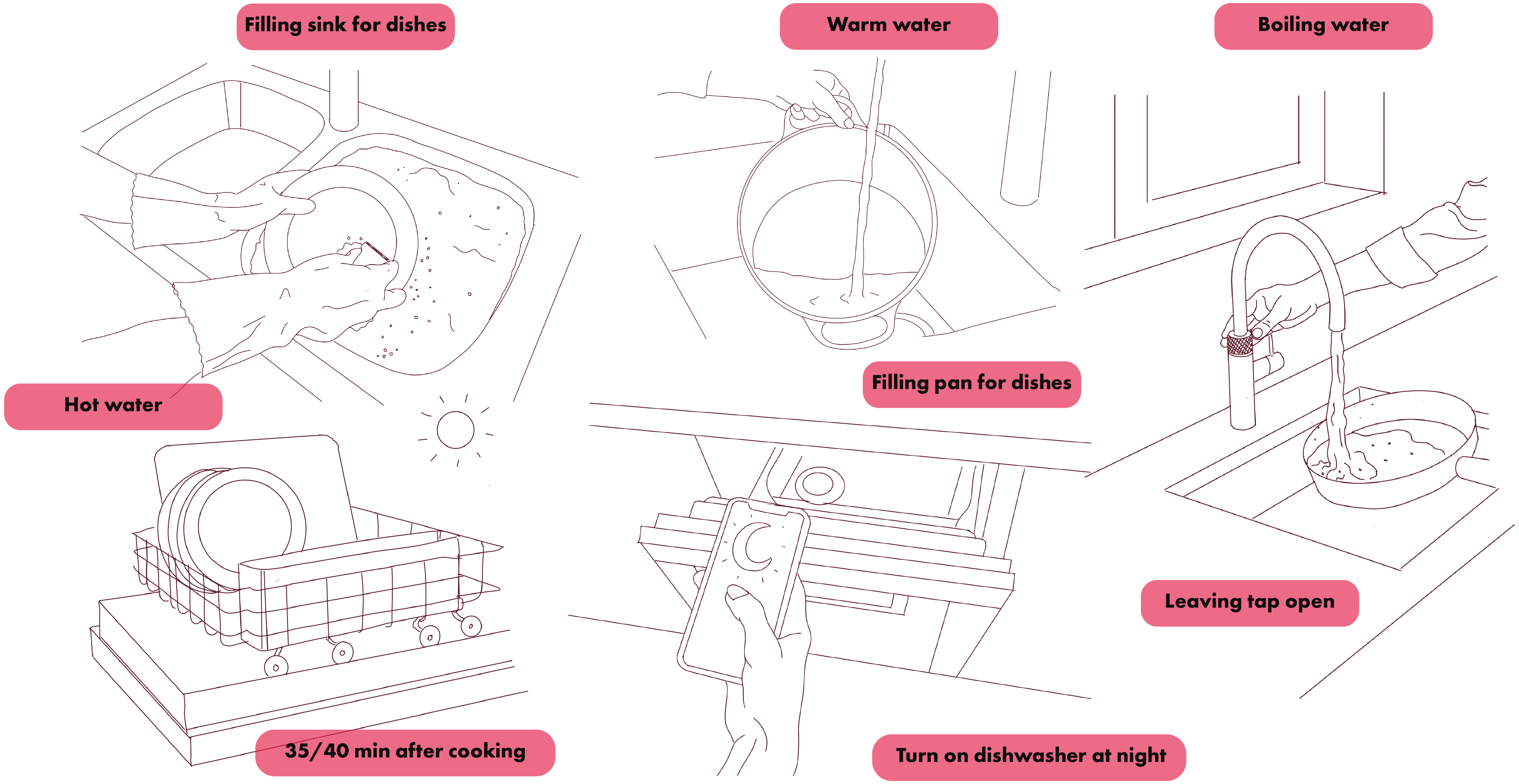
Participant 4:
- Week day 1: 1 L
- Week day 2: 0 L
- Weekend day 1: 6 L
- Weekend day 2: 0 L

Participant 5:
- Week day 1: 26.15 L
- Week day 2: 40 L
- Weekend day 1: 48.25 L
- Weekend day 2: 24 L

The outcomes of the amount of warm/hot water drained in the kitchen sink only show that there is a difference in the amount of water drained (between 0 L to 48.25 L) for the participants who did own a dishwasher. Additionally, participant 1, who does not own a dishwasher, pours significantly more hot/warm water through the kitchen sink drain. On days this participant cooked at home the amount of water drained was between 48 L and 73.5 L. Since this user test was meant for explorative research with a small research group (N=5) and different participants may have filled in the form more precisely than others, no significant patterns were found. However, this research indicates that users without a dishwasher may drain more warm/hot water in their kitchen sink than users with a dishwasher. Still, the temperature differences are not taken into account, which will influence the amount of available energy per behavior.

In addition, all user research showed that the water that is poured through the drain can be quite dirty (grey water). As mentioned before, pans and plates are rinsed and the cleaning buckets are emptied in the kitchen sink drain. Still, the bigger parts that end up in the sink are filtered by the sink strainer. This means that the water coming down the kitchen sink drain includes oils and fats, small (food or dirt) particles, cleaning detergent or dish soap, but also substances in drinking water that may cause build up of materials in the piping system.

Figure 16 highligths key outcomes from the user tapping/draining test.



(Figure 16: possible use scenarios)

BEHAVIOR DISHWASHER

According to Bakker et al (2022), the average use of the dishwasher per day differs per household (Figure 17).

HOUSEHOLD TYPE	**P** (%)	**F** (amount a day)
One-person	47	0.51
Couple without kids	78	0.36
Couple with kids	88	0.55

(Figure 17: Performance rate and frequency of dishwasher use per person in the Netherlands (Bakker et.al 2022))

An explanation for the difference in values can be that a single-person household tends to generate fewer dishes than a multi-person household.

Additionally, a dishwasher often has different rinsing programs such as eco or high-intensity programs. All have different water temperatures and running times and thus different energy use.

An interesting observation of the user test mentioned in paragraph 3.4, is that Participant 3 sets the dishwasher up in a way that the dishwasher turns on at a later moment, at night. Other participants turned the dishwasher on quickly after cooking.

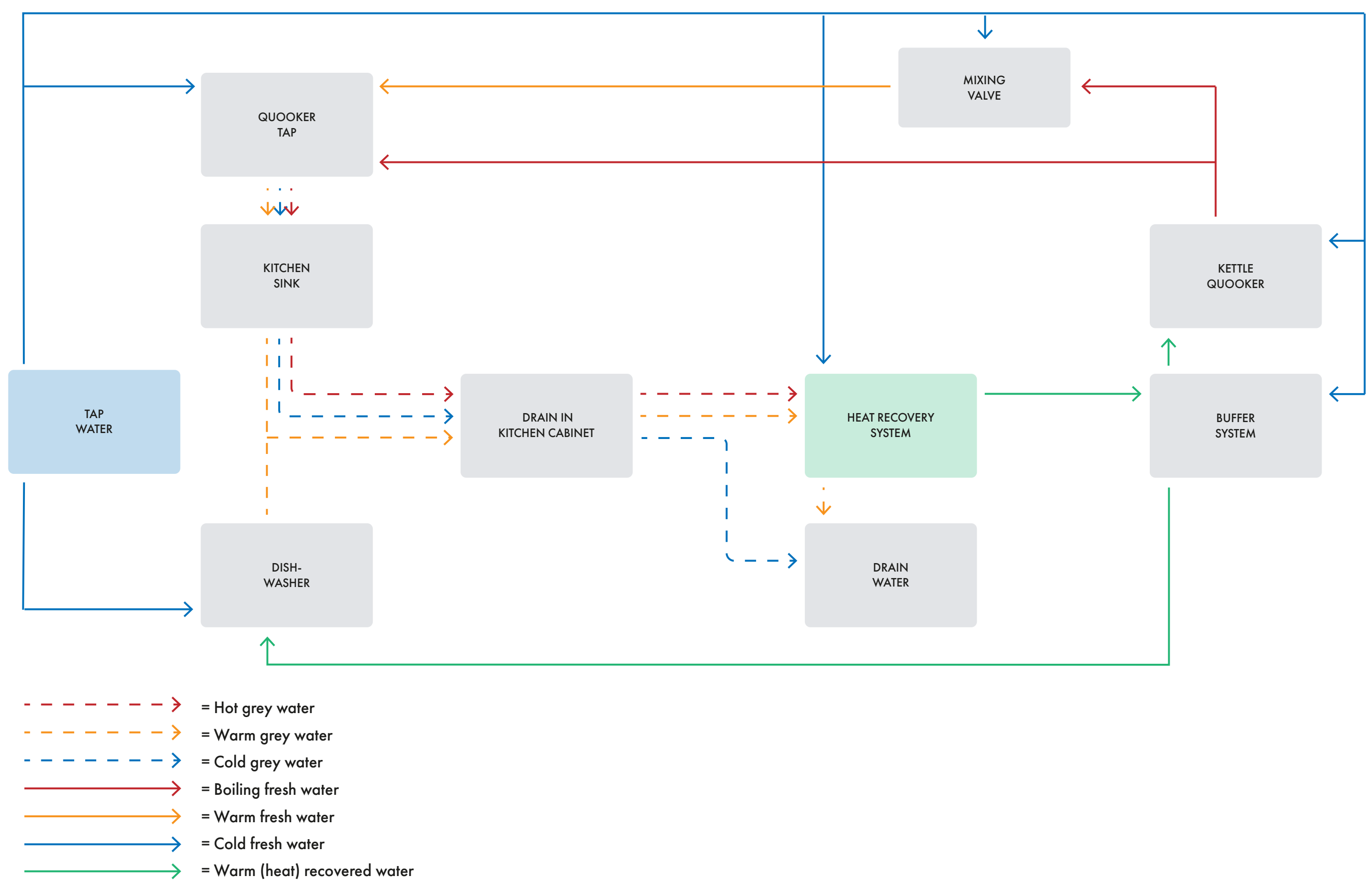
Another finding is that the Participants who own a dishwasher still use their kitchen sink for doing the dishes. They do an initial rinse in the kitchen sink for their plates and cutlery before they place those in their dishwasher and they wash their pans in the kitchen sink manually.

3.5. SYSTEM BEHAVIOR

Based on the connection between the water supply (both warm and cold) and the current Quooker systems that provide boiling water (Chapter 3.2), and the user behavior described in Chapter 3.4, the heat flow and grey water flow of a potential heat recovery system are determined. In addition, exploratory tests give an indication of the heat loss during draining water, and the water behavior and mass flow were determined.

HEAT FLOW & GREY WATER FLOW

In Figure 18, the heat- and greywater flow of the Quooker COMBI is illustrated with a potential heat recovery system that includes a heat storage buffer (see chapter 4 for technical information), the other Quooker kettle systems can be found in Appendix A4. These Figures show that the buffer system will remain the same for all three Quooker systems, only the connection to the kettle is different per system. Hot, warm, and cold greywater come from the kitchen sink drain and the cold water or water that is colder than the water in the heat buffer has to be diverted away so that it does not cool down through the HEX system. The dishwasher only drains warm greywater at different temperatures. The greywater streams coming from the dishwasher and kitchen sink drain that are hot or warm and that have a higher temperature than the water stored in the buffer are allowed to pass through the HEX system. Therefore, the system must be able to measure the temperature of the clean water in the buffer system and of the drained grey water. The clean warm heat recovered water in the buffer reservoir can be used to refill the dishwasher and the Quooker kettle (hot fill).



(Figure 18: Heat- and grey water flow of Quooker COMBI reservoir)

WATER TEMPERATURE

According to Engie (2021), the cold water net temperature in winter in the Netherlands is on average between 10-11 °C. In summer, the cold water net temperature can increase and is on average 16 degrees with peak temperatures of 21 °C. Therefore, the efficiency of implementing a heat recovery system is dependent on the time of the year.

Based on 3 explorative tests where 2.5 L boiling water was poured into a pan and then poured through a kitchen sink drain, the maximum temperature measured by a temperature sensor of the water once it hit the end of the drain tube (Figure 19) was 82.1 °C. This means that the estimated temperature of the calculation of the sink scenario in Chapter 2 of 80 °C was estimated well enough.

(Figure 19: explorative temperature test of draining 5 L of boiling water)

Figure 19 shows that the boiling water first heats the pan, then heats the sink and then heats the drain pipe. First, the 0.5 L of water in the water lock in the drain pipe is pushed out of the drain, after which the hot water comes out of the drain pipe.

MASS FLOW

During the temperature test mentioned in the previous paragraph, the mass flow rate was determined by recording the time needed for 2.5 L of the water to flow through the drain. This test was conducted three times and the average measured time was used in the calculation (Appendix A6). The flow rate of the water in this scenario was 0.19 L/s.

TURBULENT OR LAMINAR

Another observation during the temperature test was that the water would not flow completely laminar or turbulent out of the drain pipe: the water would flow through a spiralling movement out of the pipe, sticking to the inside wall of the drain pipe. In the middle of the pipe, there was air, no water. This effect may be caused by the water lock that was located between the kitchen sink and the end of the kitchen drain pipe. The water first entered a bigger pipe, then it was narrowed down and bent in direction of the water lock and after the water lock it again entered a bigger pipe. As a result: the water came out spiralling with air in the middle of the pipe.

According to a research engineer at Quooker, the water did not flow fast enough to call the flow turbulent. However, the water did not come out of the drain pipe in a straight line: it came out spiralling. Therefore, the water stream could not be called completely laminar either. As a result, the flow around the walls is relatively higher, which could be beneficial for the heat transfer rate.

DISCOVER

04

TECHNOLOGY

Heat recovery can be achieved through different methods. Different opportunities and drawbacks arise if heat is recovered by changing the modem (converting heat to energy) or by maintaining the modem (heat to heat). This chapter discusses the different options, opportunities and drawbacks of heat recovery.

KEY INSIGHTS

- Sensible heat storage is desired over latent heat storage.
- Water is the most suitable option as the medium for heat transfer in the kitchen scenario.
- Since warm/hot water and cold water are not always channelled simultaneously through a HEX system in this kitchen context heat recovery scenario, a heat storage buffer system is essential.
- A buffer system and HEX system can be combined into one (shell and coil principle).
- it is desirable to look into dirt separation options or a system with a larger diameter to reduce the risk of clogging or fouling.
- As the heat recovery system needs to fit in the kitchen cabinet under the sink, the use of a shell and tube HEX system for this project is not feasible.
- To reach higher heat transfer efficiency, the tube of a HEX where heat is exchanged over, should be longer.
- The smaller the diameter of a tube where heat is exchanged, the higher the heat transfer efficiency is over a smaller volume space.
- The buffer reservoir of Quooker can be reused as a heat buffer system.

4.1. HEAT TO ENERGY

One of the opportunities for heat recovery is to transfer heat into energy. Energy could potentially be used to reduce the energy consumption in the kitchen. In this chapter, the amount of energy that can potentially be converted from warm wastewater in the kitchen context is discussed. Additionally, the options for heat recovery with the use of energy are elaborated.

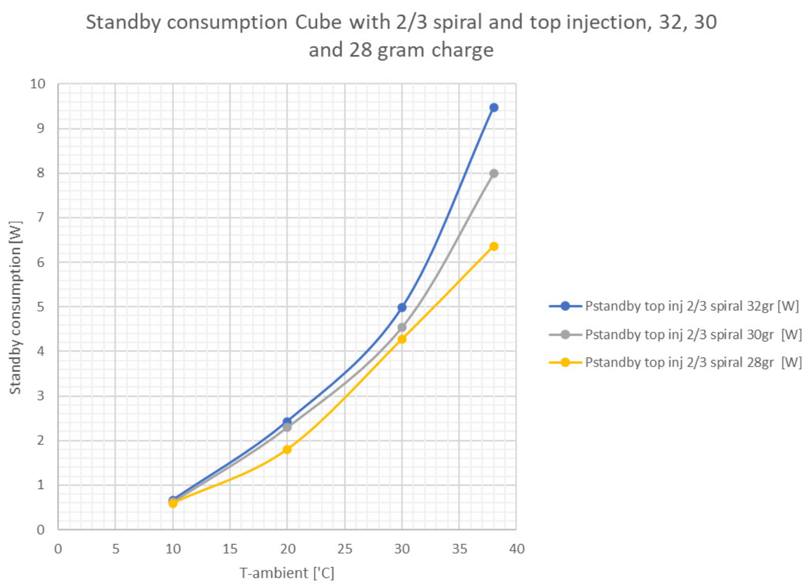
REDUCTION ENERGY CONSUMPTION

The reduction of energy consumption can be achieved in different ways. One of the options is to use the generated energy as an energy source for Quooker devices to work. In that way, Quooker devices would use less energy and heat would be recovered for energy reduction purposes.

A way to reduce the energy consumption of Quooker devices is to look into the factors that influence the higher energy consumption of the devices. This method of using a heat recovery system that transfers heat into energy can be seen as a prevention of higher energy consumption of Quooker devices. Chapter 3 elaborates on the different Quooker devices. Since the Pro3, COMBI and COMBI+ are well-insulated devices, the influence of the surrounding environment on energy consumption is minimal. For the CUBE, however, figure 20 shows that the ambient temperature significantly influences the standby consumption of the CUBE. According to a research engineer at Quooker International B.V. , the CUBE produces heat that is spread into the closed environment of a kitchen cabinet, this ambient temperature is measured to be relatively high and can quickly reach higher temperatures.

"The energy efficiency of the CUBE is determined by the ambient temperature the device has to cool against. This, whilst the CUBE itself produces heat into the small space of a kitchen cabinet"- Research Engineer at Quooker International B.V., 2023

Figure 20 shows that the higher the ambient temperature, the faster the standby consumption rises. The standby consumption is almost doubled (5W to 9.5W) when the standby consumption is compared between an ambient temperature of 30 °C and 38 °C (8 °C temperature difference).



(Figure 20: Influence of ambient temperature on standby consumption of the CUBE)

PELTIER

Peltier elements, known as Thermal Electric Generators (TEG), have the main function of creating a thermal difference between two parts once electrical energy is applied to it. However, these devices can also be used to convert heat to electrical energy through the so-called Seebeck effect. This effect generates energy once a thermal difference is created between two plates.

TEGs are commonly used for heat recovery, for stove fans and to enhance the fuel efficiency of automobiles (ATGs). One of the significant benefits of TEG systems is their stability, reliability, and capacity to function for several years without requiring maintenance (Faghri & Zhang, 2006). Despite these benefits, TEG systems are known for their relatively low efficiency (Tohidi et al., 2022).

More work is required if thermoelectricity is to compete with other technologies. It is important to note that most potential uses for thermoelectric generators (TEGs) rely on the high availability of heat at medium to low temperatures (Faghri & Zhang, 2006).

An experiment where water at melting point temperature and boiling water were connected to a Peltier element shows an indication of what the potential is of converting heat to energy from hot water is in the kitchen context (RimstarOrg, 2013).

ΔT = 100°C	0.143 A	0.854 V	0.122 W

(Figure 21: Outcomes Seebeck effect of connecting boiling water and ice cold water to a Peltier element based on an experiment of RimstarOrg (2013))the CUBE)

Given the data from Figure 21, 0.122W can be generated with a temperature difference of approximately 100°C. With the average standby use of a Quooker PRO3 of 10W, this converted amount of power is too minimal to speak of valuable heat or energy recovery: around eighty Peltier elements are necessary to bring the stand-by use to net zero (Quooker, n.d.). This amount of Peltier elements is too much to make a valuable difference in energy, cost and carbon footprint with heat recovery.

Still, there is the option to reduce the standby consumption of the CUBE by using the recovered energy of a Peltier element for cooling purposes of the kitchen cabinet. However, the power output of a Peltier element is so low that one Peltier element cannot power a small computer fan. Additionally, the kitchen cabinet under the sink lacks cold surfaces. Effective cooling of the kitchen cabinet by a fan requires a sufficient cold surface to cool on, therefore this option is rejected for this project.

4.2. HEAT TO HEAT

Heat recovery involves transferring heat between two materials. This method does not require a conversion, therefore there is lower energy loss than using a Peltier element for heat recovery. In this paragraph, different aspects and options of heat exchangers are discussed.

HEAT STORAGE

As mentioned in Chapter 3, the moment warm grey water is drained and cold water is requested for refilling either the dishwasher or the Quooker kettle is not always simultaneous. Therefore, a heat exchanging system requires a buffer system, where the recovered heat is captured for later use.

SENSIBLE HEAT STORAGE

Sensible heat storage is the energy stored by changing the temperature of the storage medium. The phase of the material can differ from solid, liquid or gas.

$$Q = m * c_p * \Delta T \qquad (1.1)$$

Where Q is the sensible heat stored in a material, m is the mass of the material, c_p is the specific heat and ΔT is the temperature difference between two materials.

Equation 1.1 shows that the temperature difference is directly related and in proportion with the sensible heat storage.

Sensible heat storage has multiple benefits. These storage systems are known for their stability, large temperature ranges, and often low-cost materials.

Common materials used for sensible heat storage are Water, Thermal oils, earth materials, and concrete. For lower temperatures (0-100°C), water is commonly used. The other materials are often used at higher temperatures (Alva et al., 2018).

Since the temperature difference for this heat recovery project will not exceed 100°C, water as a sensible heat storage medium is best suitable. Using water has merits: it is inexpensive, not harmful and accessible.

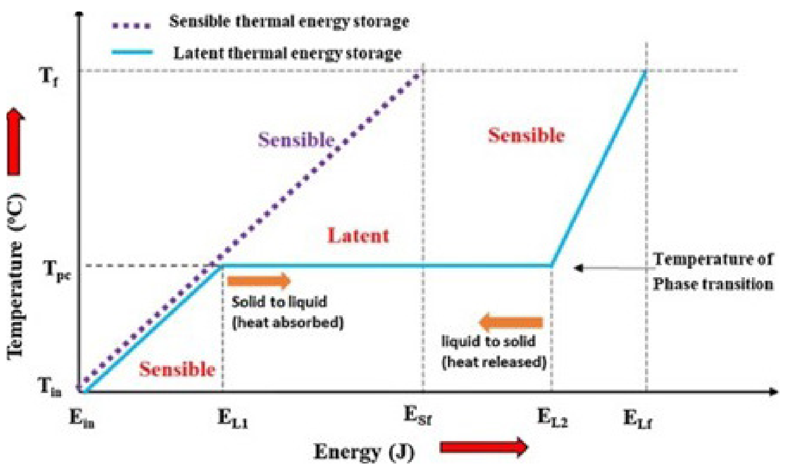
However, sensible heat storage also has a drawback: compared to latent heat storage, sensible heat storage has two orders of magnitude lower specific heat capacity.

LATENT HEAT STORAGE

With latent heat storage, heat is stored using the phase change of a material.

$$Q = m * L \qquad (1.2)$$

Where Q is the heat stored in a material, m is the mass of the material, L is the specific latent heat.
The most common phase transition used is from solid to liquid because of the similar volume size. Various materials, organic and non-organic, can be used as phase change materials (PCMs) including paraffin, sugar alcohols, eutectics, fatty acids and salt hydrates. PCMs provide a higher storage density compared to sensible heat storage and can charge/discharge within a narrow temperature range (Figure 22).



(Figure 22: Phase transition profile of phase change material (Reddy et al. (2018))

However, PCMs have a low thermal conductivity which necessitates complex heat exchanger design. Compared to a sensible heat storage medium like water, they are also expensive and have only been tested in small-scale configurations, which results in a low Technology Readiness Level (TRL). Additionally, latent heat storage requires a stable temperature release. To find the right PCM material for an application, it is important to find one that has its change in phase around the heat release temperature of the heat source. Given the different temperatures in which heat is released in the dishwasher and sink scenario mentioned in Chapter 3, latent heat is less desirable for a heat recovery system for warm wastewater in the kitchen context.

HEAT STORAGE CHOICE

As mentioned earlier in this paragraph, sensible heat storage is prefered over latent heat storage for this context. Additionally, water to water heat transfer is chosen to be the medium for this context.

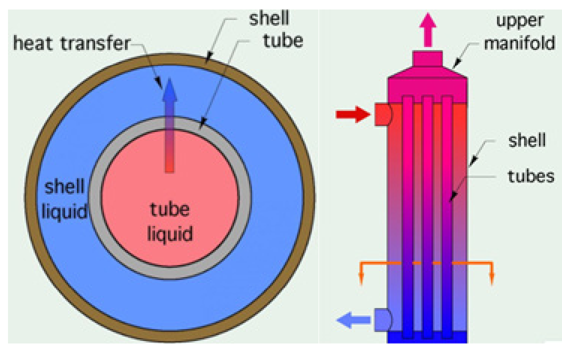
HEAT EXCHANGERS

To transfer heat from one material to another material, heat exchangers are commonly used. There are different heat exchangers (HEX) for different purposes and different material phases. Since this project is about sensible heat exchange from water to water, commonly used heat exchangers for liquid-to-liquid are discussed in this paragraph (Caleffi Idronics, n.d.), (Selimli et al., 2019).

SHELL AND TUBE

The working principle of a shell and tube heat exchanger moves fluid A through one or more tubes with fluid B moving in a contrary direction (between and) around the tube(s) (Figure 23).

Shell and tube heat exchangers, such as shower heat recovery systems, are often large installations since they require more metal volume than other liquid-to-liquid HEX systems with comparable capacity (Caleffi Idronics, n.d.). A plate and frame HEX (further elaborated on in this paragraph), for example, has up to 5 times smaller volume than a shell and tube HEX with similar efficiency (Central States Industrial Equipment & Supply, 2022). However, shell and tube HEX systems are generally less prone to fouling or clogging than plate and frame HEX systems due to an often higher tube diameter size (Central States Industrial Equipment & Supply, 2022).

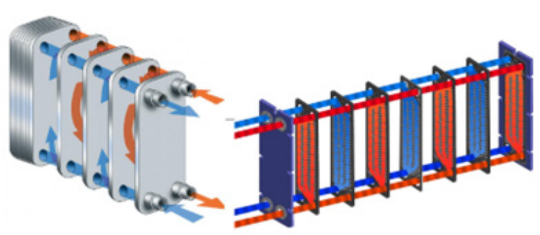


(Figure 23: shell and tube HEX working principle, a top-view and side-view (Caleffi Idronics, n.d.))

As the heat recovery system needs to fit in the kitchen cabinet under the sink and a higher heat transfer efficiency is desired, using a shell and tube HEX system for this project is not feasible.

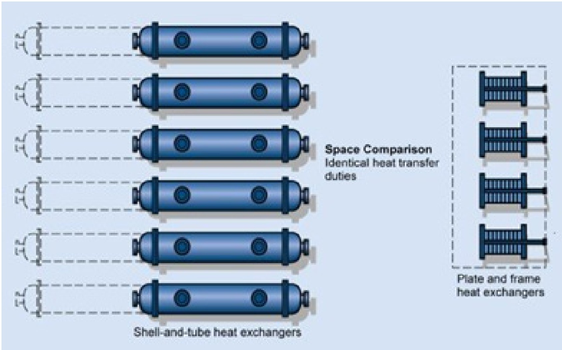
PLATE AND FRAME

In a plate and frame HEX, fluids A and B flow through different alternating channels in a stack of plates (figure 24). According to a HEX expert from HEX-rentals (2024), these channels are relatively small and have an average diameter of 5mm for systems that would be suitable to fit in a kitchen cabinet. This small diameter increases the risk of clogging and fouling of particles in the channels (Chapter 3). Therefore, the main disadvantage of using a plate and frame HEX system is the high chance of fouling and clogging compared to a HEX system like a shell and tube HEX system.



(Figure 24: plate and frame HEX working principle (Adler et. al, 2005))

Additionally, the expert (2024) mentions that the small diameter of the inlet pipe of the Plate and Frame HEX results in an additional water pressure needed for (clean) water to be able to enter and leave the HEX system.
Nevertheless, Plate and frame HEX are known for their high performance in heat transfer compared to their size (Figure 25). Since these HEX systems are modular in size, the capacity, efficiency and size can be increased or decreased by changing the number of plates. In modular systems, each plate can be cleaned separately after fouling or clogging. However, this requires the whole HEX system to be disassembled. Therefore, for this project that contains heat recovery of grey water, it is desirable to look into dirt separation options or a system with a larger diameter to reduce the risk of clogging or fouling.

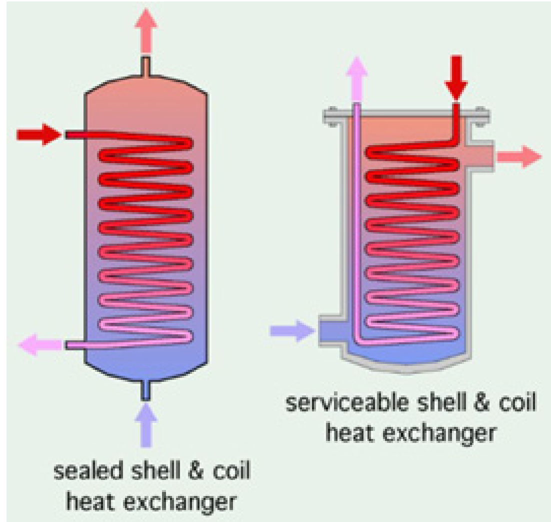


(Figure 25: space comparison of a shell and tube HEX and a plate and frame HEX with similar efficiency)

In a plate and frame HEX, fluids A and B flow through different alternating channels in a stack of plates (figure 24). According to a HEX expert from HEX-rentals (2024), these channels are relatively small and have an average diameter of 5mm for systems that would be suitable to fit in a kitchen cabinet. This small diameter increases the risk of clogging and fouling of particles in the channels (Chapter 3). Therefore, the main disadvantage of using a plate and frame HEX system is the high chance of fouling and clogging compared to a HEX system like a shell and tube HEX system.

SHELL AND COIL

Shell and coil HEX systems are not as commonly used as shell and tube and plate and frame HEX systems in liquid-to-liquid systems. This is a result of their limiting amount of coil surface area compared to the overall size of the HEX system. The volume of the liquid in the shell is relatively larger than the volume of the liquid in the coil (Caleffi Idronics, n.d.). Nevertheless, these systems can be useful when the HEX system also serves as a heat storage device. As mentioned in Chapter 3, an additional insulation tank is needed to bridge the time gap between tapping hot/warm water and draining hot/cold water. Therefore, the working principle of a thermal storage device in this shell and coil system is interesting for this project.



(Figure 26: shell and coil heat exchanger working principle (Calefi Idronics, n.d.))

FIN AND TUBE

In an experimental study about the performance of a fin and tube HEX tank attached to a dishwasher, the thermal storage system of a shell and coil HEX and the plates of a plate and frame HEX, serve as an improvement in heat transfer surface of a frame HEX, are combined (Selimli et al., 2019) (figure 27). The benefits of this combination are a higher heat transfer surface compared to a simple shell and coil HEX system. Additionally, this system allows a time difference between incoming warm/hot water and incoming cold water to still work for heat transfer. This is desired for the HEX system of this project. Still, the fouling and clogging risk as earlier described is an issue here: the warm/hot grey water would still move through tubes with a significantly smaller diameter than the diameter of a kitchen sink drain pipe.

(Figure 27: Fin and tube heat exchanger in heat exchange tank (Selimli et al., 2019).

In this particular scenario, it is common for the demand for cold water to not be simultaneous with the discharge of cold water. In this case a heat exchange system without a counter-current principle of warm and cold water that flows simultaneously is desirable. Implementation of such a system requires a compromise in efficiency, as the warm water flow has to warm up a bigger water volume with less counterflow. Additionally, the temperature difference between cold and warm water reduces when the cold water has already undergone partial heating through prior usage of the heat-exchanging system. Furthermore, warm grey water discharged at a temperature lower than that of preheated water becomes ineffectual. Nevertheless, the installation of a buffer system remains important to mitigate the non-simultaneous water flow between water consumption and provision. Furthermore, the problem of drain water with a lower temperature than the heated up water will arise in both scenarios.

HEAT BUFFER

As mentioned in earlier paragraphs, the moment of tapping warm/hot water is not always simultaneous with the moment of draining hot/warm water. Therefore, a heat buffer is desired to slow down the heat loss process of captured heat over time.

BUFFER RESERVOIR

Such a heat buffer can be created by e.g. the use of an insulated tank. For insulation, there are different methods available with different insulation materials. However, Quooker already manufactures insulated kettle tanks and thus has machines and materials at its disposal that can produce vacuum-insulated tanks. Therefore, for this project, it is assumed that a vacuum-insulated tank is the best option for Quooker to use as a heat buffer system (Quooker, n.d.).

DEFINE

05

DESIGN DIRECTION

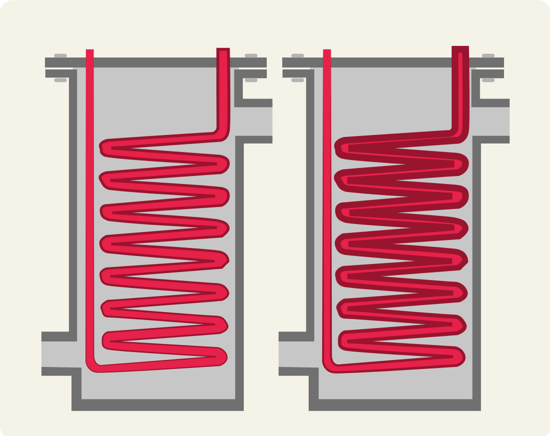
Designing a heat recovery system for grey water in the kitchen context has different hazards and aspects to take into account. All hazards and factors together bring complexity. In this Chapter, different important factors and the project's complexity are elaborated. Lastly, different project directions are discussed and the final direction and approach for this project is defined.

KEY INSIGHTS

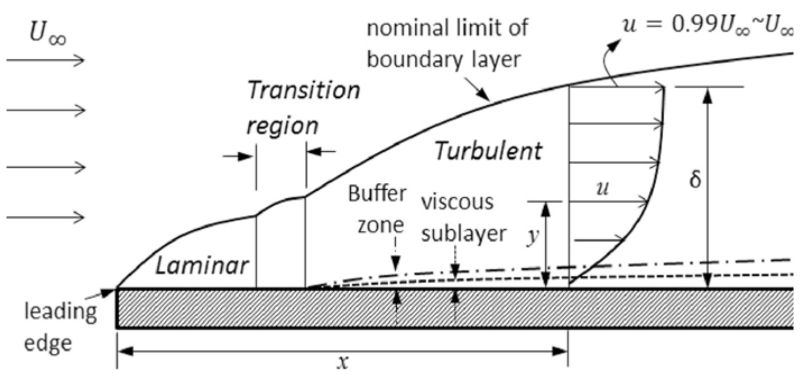
- Designing a heat recovery system for grey water in the kitchen involves numerous hazards and factors, including fouling and clogging, which add complexity to the project.
- Small tubes in heat exchangers are prone to fouling (build-up of materials) and clogging (obstructions), reducing efficiency over time
- Both turbulent and laminar flows can contribute to fouling, with turbulent flows increasing the risk through the viscous sublayer and laminar flows allowing particle deposition
- Heat exchanger efficiency can be improved through higher temperature differences, turbulent flow, longer tubes, smaller diameters, increased surface area, and prevention of heat loss.
- Two main directions emerged: adding a filter system or redesigning the heat exchanger with larger tubes to mitigate clogging risks. The project focuses on the second directoin.
- Three design principles were identified: a simple shell and coil with minimal bends, a standard shell and coil, and a fin and tube heat exchanger in a tank.
- Principle 1 was chosen for further development due to its simplicity and lower risk of fouling/clogging despite lower efficiency. Iterations on Principle 1 include testing U-shaped and W-shaped tube configurations to improve heat transfer efficiency.
- The main challenge is balancing simplicity and efficiency, given limited available energy and user desires for low initial cost and acceptable payback time.

5.1. FOULING AND CLOGGING

The often small tubes in heat exchangers for small scale applications are prone to fouling and clogging (Chapter 3 & 4). Fouling is the build-up of materials like bacteria, residues, and salts on the walls of the heat exchanger (Figure 28). Clogging refers to an obstruction in pipes, which can be caused by fouling. In this paragraph, fouling and clogging is elaborated on.



(Figure 28: fouling in a heat exchanger)



(Figure 29: viscous sublayer increases when water mass flow increases, Shahmohamadi and Rashidi (2017)).

Fouling can reduce the water flow or can cause total blockage. Additionally, the efficiency of the HEX system will decrease over time if the HEX system starts fouling and clogging over time.
Next to the 'dirtiness' of the water in the HEX system being a factor that can increase the chance of fouling and clogging, turbulence and thus a higher flow and surface roughness rate can also increase the chance of fouling. According Characklis (1981), fouling can occur in the viscous sublayer of a turbulent water flow (Figure 29).

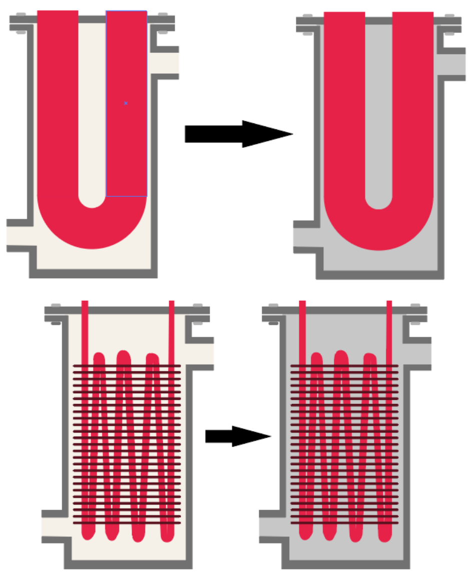
However, as mentioned in Appendix A7, a slow, laminar flow can also result in particles in the water sinking and creating a sludge layer and oils floating to the surface of the water. Using a laminar flow to separate parts and oils from water is used in bigger water purification systems and requires time for the parts to separate. Nevertheless, a laminar flow can also cause fouling/clogging of a system.
Additionally, fatty/oily particles in water can solidify or clot once the water temperature decreases. This also results in a higher risk of fouling and clogging of fatty/oily particles to pipe surfaces. Warm water in a HEX system is known to decrease in temperature, so this issue will remain.

5.2. EFFICIENCY

As mentioned in Chapter 4, the efficiency of heat exchangers can increase by changing different parameters. Some important factors to increase the efficiency of heat exchangers are:

1. Higher temperature difference
2. Turbulent flow: high mass flow: high Reynolds number
3. Longer tube
4. Smaller diameter of the tube
5. More surface area to transfer heat over
6. Prevention of heat loss

Nevertheless, the HEX system first has to heat up, so the efficiency will also be dependent on the size of the system and the intent of use.



5.3. PROJECT DIRECTION

In this paragraph, different directions for a heat recovery solution are elaborated. Finally, one direction is chosen to continue this project with.

To reduce the risk of fouling or clogging, different approaches are possible. In a brainstorming session with students from IDE, TU Delft, different causes and options for the prevention of fouling and clogging were covered (Figure 30).

(Figure 30: Brainstorm ideation session with students for possible solution directions of the fouling and clogging problem)

Before this brainstorming session, the students were given important information about the project (Appendix A8). During the ideation session, many ideas arose, going in multiple directions. After the brainstorming session, it was clear that there should either only be an additional filter system to filter the water before going into the HEX system, or there should be an adjustment to one of the existing HEX systems so that a HEX system is less prone to fouling or clogging, or a combination of both. Research to other liquid-to-liquid product applications at home show that laminar blackwater flows can be filtered (passive) (Appendix A7). However, Chapter 3 outlined that the water behaviour is neither fully laminar or turbulent.

Additionally, it became clear that for most of the solutions for the separation of particles/oils and water, either solutions with high cost/technology were suitable or lower cost solutions that required a slow, laminar water flow were suitable. Since the water flow in the kitchen drain system initially runs spiraling through the drain pipe, separation methods that require a low water flow rate are nearly impossible. Only if the water can be slowed down somehow, this would be possible. However, slowing water down often requires time, and the water's heat can get lost in the environment over time.

1. A water from oil/dirt separation solution that is an addition to an existing heat exchanger that probably has sufficient efficiency. A possible solution could be an additional water filter system that is cheap, fast (little heat loss) and has little maintenance.
2. Changing an existing heat exchanger for the kitchen context so that the risk of clogging/fouling is reduced. Testing different prototypes with bigger tubes/bigger loops, which makes clogging/fouling less of a hazard, than the currently existing models can show the effect on heat transfer efficiency.

Both options are important and interesting to investigate to be able to provide Quooker with a full understanding of whether implementing a heat exchanging system for warm wastewater in the kitchen is valuable. However, both options require a different approach and therefore this project only focuses on option 2.

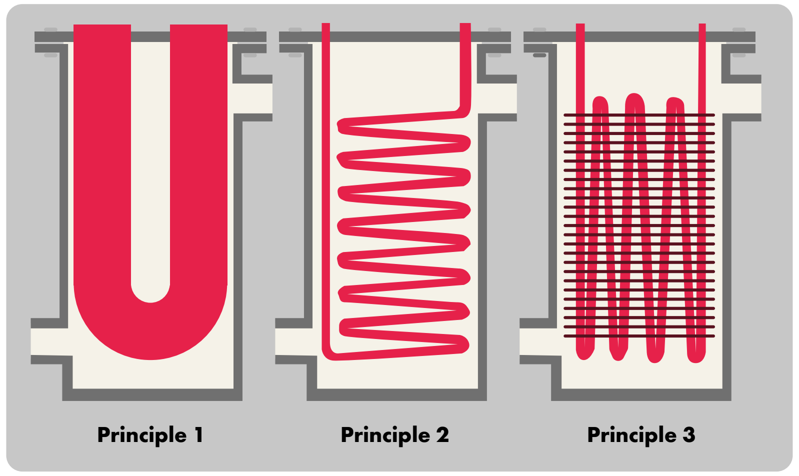
5.4. APPROACH

For a heat recovery system to be feasible, desirable and viable, different aspects should be considered. Some of these aspects are contradictory to one another, which results in the complexity of the design of a heat-recovering system in the kitchen context (Chapters 3, 4 & 5).

Based on the findings, three principles were found to be interesting for the kitchen context (figure 31). All three principles have the shell and coil principle described in chapter 4. Principle one is a shell and coil-inspired principle with the HEX system having the diameter of the drain pipe in the kitchen and only one bend to reduce the complexity of the system. Principle 2 is exactly the working principle of a shell and coil heat exchanger and principle 3 is a fin and tube heat exchanger attached in a tank.

The efficiency of a heat exchanger can not only be seen as the heat transfer rate but also covers the speed in which heat is transferred from one material to the other. As mentioned in paragraph 5.2, turbulent water is more desirable for a higher efficiency rate of most HEX systems. This means that a higher heat transfer rate can be reached in a shorter period. Contrary to other heat exchanging applications, which e.g. use a counterflow principle to transfer heat faster, a heat exchanging system for the kitchen context does not have to be as efficient in terms of heat transfer speed. This is a result of warm/hot water drained in the kitchen often not occurring simultaneously with tapping hot/warm water. This 'waiting' time between the supply and request of hot/warm water in the system can be used to transfer the heat from drained water to the drinking water. This allows a heat exchanger in the kitchen context to have different specifications than most time-efficient heat exchangers.

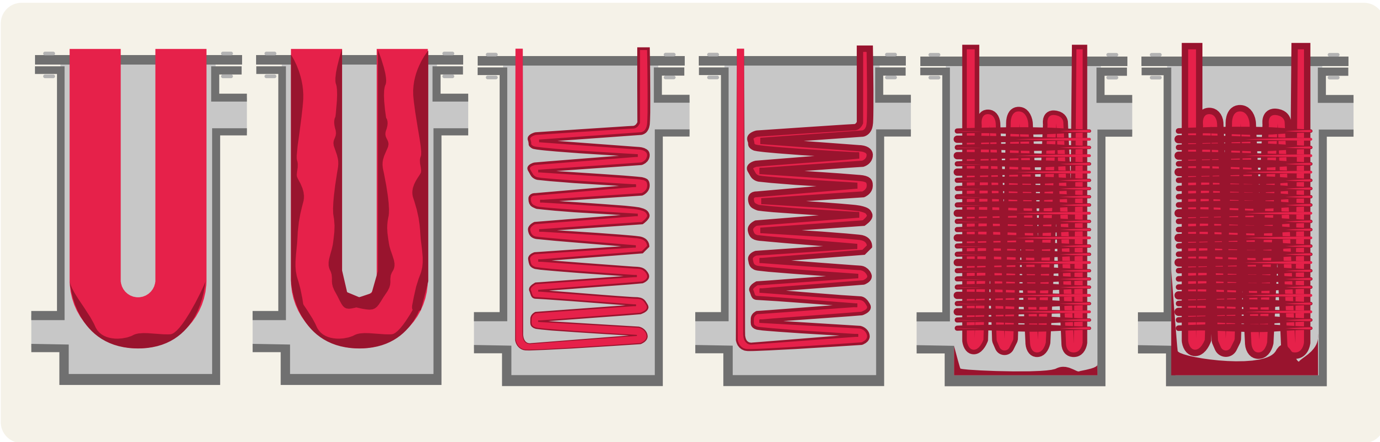
Looking at the difference in terms of efficiency, principle 1 is likely to have the lowest efficiency rate and speed compared to principles 2 & 3. This is a result of the bigger diameter of the HEX tube, the shorter tube length, and the heat transfer surface.



(Figure 31: three different principles for heat recovery)

Nevertheless, concepts 2 and 3 are likely to require an additional pump to push the grey water through the small tube diameter. Next to the already higher expected price due to more complexity of the system of principles 2 & 3, the pump will increase the price of principles 2 & 3 more.

Unfortunately, higher turbulence also increases the viscous sublayer of a tube, which can result in fouling of particles on the walls of the tube. Additionally, smaller tube diameters can increase the risk of fouling/clogging. Therefore, over time, concept 3 is expected to be most prone to fouling/clogging, followed by concept 2. Due to the bigger size of the diameter of the HEX in principle 1, this option is expected to experience the least problems with fouling/clogging over time (Figure 32).
Nevertheless, the position of the drinking water and grey water can be swapped. In this case, the grey water would be positioned in the buffer reservoir and the drinking water would be flowing through the small pipes. Then still, there is a need for a pump to push the water through the pipes and the risk of fouling/clogging will move from the inner side of the tubes to the inner side of the reservoir and outer shell/surface of the HEX system. Both are still not beneficial.



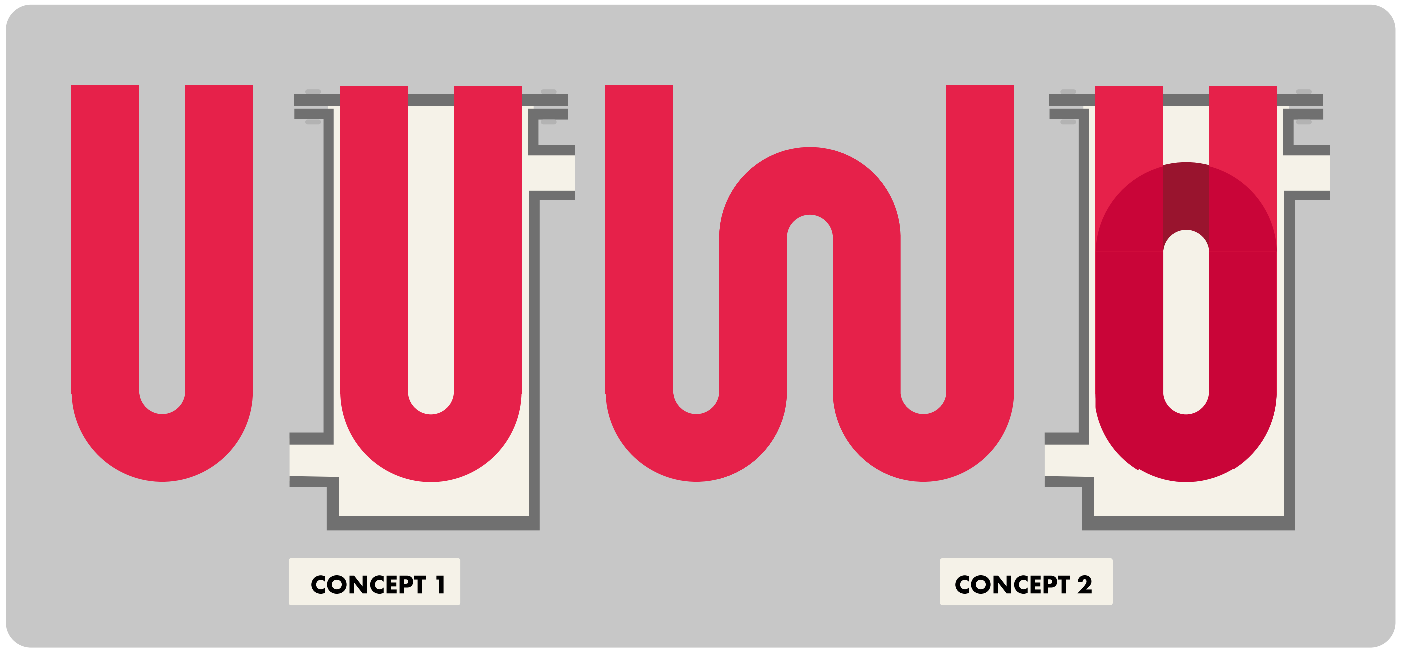
(Figure 32: risk of fouling/clogging over time in all principles)

Figure 33 highlights that the main drawback of choosing the more simplistic principle 1 is giving in on efficiency. Even though the system's efficiency seems to be the most important factor for choosing an HEX system, the user desires mentioned in Chapter 3 show that the selling price and payback time of a product is of important for users to think of buying a product. Therefore, the initial cost of producing this product should be as low as possible. A lower initial product price results also in a lower necessity for efficiency. This lower initial product price can also have a beneficial effect on the payback time, but this is highly dependent on the system's efficiency too.

Since the benefits of a simpler heat-exchanging principle with a bigger tube diameter outweigh the drawbacks, principle 1 was chosen to be the most promising principle to continue the project with.

However, an iteration on principle 1 was chosen to be made to investigate whether a longer tube length would have enough benefit in terms of heat transfer efficiency. Therefore, the following two concepts were created to further develop and test:

(Figure 33: expected benefits and drawback of the simplicity of principle 1 compared to principles 2&3)



(Figure 34: U-shaped tube for concept 1 and W-shaped tube for concept 2)

As mentioned in Chapter 2, the amount of available energy is limited and therefore the main challenge of this project is to find a balance between simplicity and efficiency of the HEX system.

As a starting point, the heat transfer coefficient of the system and the influences of important parameters, calculations were made (Appendix A9). These calculations are based on the calculated mass flow in chapter 3 and use an estimation of the system parameters like tube length (0.8 m) and diameter (0.035 m). The heat transfer coefficient for this scenario was found to be 357.

However, chapter 3 described that the actual flow of the water in a drain pipe was observed to behave in a way both laminar and turbulent. Additionally, these calculations do not include any change in the direction of the pipe (bends). Lastly, these calculations do not take e.g. the heat spread in the water in the buffer basin over time into account. Therefore, it was decided that prototypes should be created and tested to find a more accurate answer on the heat transfer rate.

Both U & W shaped concepts are developed into prototypes to test the systems on their efficiency and to make a choice between both concepts.

Tube cross-sectional area and the Reynolds number:

$$Ac := \pi * \frac{d^2}{4} \qquad (2.1)$$

$$Red = \frac{\left(\frac{mdot}{Ac}\right)*d}{mub} \qquad (2.2)$$

Since Re <2300, the flow is laminar. Therefore the following equation applies for the corresponding average Nusselt number for a tube of length L:

$$Nud = 3.66 + \frac{0.065\left(\frac{d}{L}\right)Red*Pr}{1+(0.04(\left(\frac{d}{L}\right)Red*Pr)^{\frac{2}{3}}} \qquad (2.3)$$

Correction of variables (Table A8 from Basic Heat And Mass Transfer (Mills, 2013)):

$$cor = \left(\frac{mus}{mub}\right)^{-0.11} \qquad (2.4)$$

The corrected Nusselt number:

$$Nudcor = Nud * cor \qquad (2.5)$$

Convective heat transfer coefficient:

$$hc = \left(\frac{k}{d}\right) * Nudcor \qquad (2.6)$$

With a constant shell temperature, the following equation applies:

$$Tbout = Ts - (Ts - Tbin) * \exp\left(-\frac{hc*2*\pi*0.5*d*L}{mdot*cp}\right) \qquad (2.7)$$

DEVELOP

06

PROTOTYPING & TESTING

In this chapter, two prototypes (U-shaped & W-shaped) are created. In an A/B test, both prototypes are tested on how well they transfer heat and evaluated on their difference in cost price and on the outcomes of the test. Finally, a list of requirements and wishes is presented.

KEY INSIGHTS

- Two prototypes, U-shaped and W-shaped, were developed to evaluate heat transfer efficiency, cost, and performance.
- Tests were conducted using two scenarios with boiling water to measure heat transfer at various water depths.
- The COMBI(+) reservoir was selected due to its compatibility with the required tube dimensions.
- A 35 mm diameter copper tube was chosen to fit within the reservoir while maintaining effective heat transfer.
- Copper was chosen for its heat transfer properties, cost-effectiveness, and safety for drinking water. In addition this material mitigates the risk of galvanic corrosion and failing with unclogging agents.
- The W-shaped prototype had a faster heat transfer rate but required more complex manufacturing and higher material costs. The U-shaped prototype was more cost-effective, with a lower estimated purchase price and reduced long-term heating costs.
- The U-shaped prototype was selected due to its lower cost, simpler design, reduced material usage, and lower carbon footprint. This choice also accounted for better cleanability, reduced fouling risk, and overall longevity of the product.

6.1. BUFFER SIZE

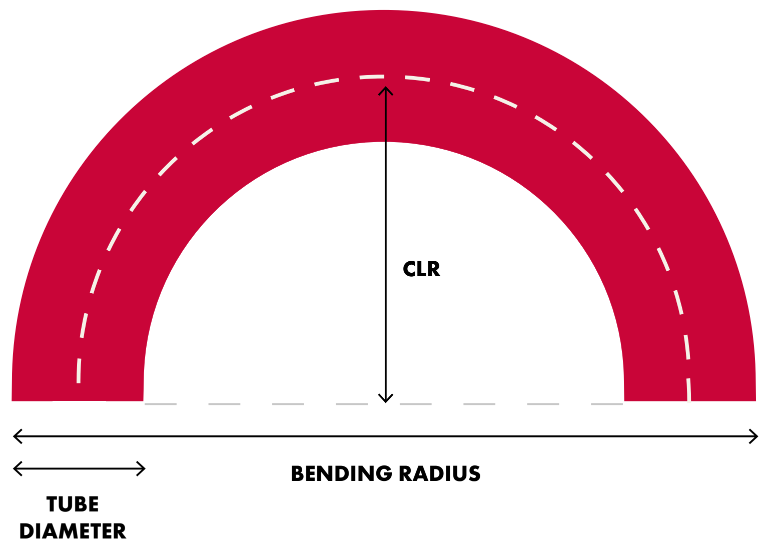
As mentioned previously, one of the buffer reservoirs of the Quooker kettles are reused. The PRO3 and COMBI reservoirs differ in size. In this paragraph one of the reservoirs is chosen to use for prototyping and conceptualization.

Quooker is specialized in products that retain heat, such as the PRO3 and COMBI. Reusing materials can lead to future opportunities for e.g. refurbishment of parts or reducing the initial cost of a part. Additionally, reusing parts result in Quooker having to make fewer changes to its current production line. By reusing the same parts as the existing Quooker products as much as possible, a tank that Quooker already uses for the PRO3 or COMBI(+) is taken as a starting point for testing and further development of the concepts.

In kitchen plumbing, the diameter of a drain pipe is typically 40 mm. For the U-shaped concept, one bend must fit in the tank ,whereas for the W-shape concept, the design requires two bends that should fit in the tank. The prototype should include a bended tube of which the minimum bending radius is of importance. The minimum bending radius of a pipe depends on the material characteristics and the outer tube diameter. While the minimum bending radius can vary, it can generally estimate using a rule of thumb (figure 35)

For a tube with the average drain pipe diameter of 40 mm, the minimum bending radius would be between 160 and 200 mm. As described in Chapter 3, both the PRO3 and COMBI(+) buffer reservoirs do not have a large enough diameter to fit in the bended 40 mm diameter tube in case the minimum bendin radius is 200 mm. Therefore, the COMBI(+) reservoir was chosen as buffer reservoir.
Therefore a smaller tube diameter is used (35 mm) so that both the U-shaped and W-shaped HEX fit in the largest size reservoir of the COMBI(+) to maintain the biggest tube diameter size possible.

$$Min.\,bending\,radius = tube\,diameter * (4\,or\,5)$$



(Figure 35: minimum bending radius tube)

6.2. TUBE

Since the tube in the prototype functions as the heat exchanger and gets in contact with drinking water, the tube has to match different requirements. The material of the tube is chosen by first considering materials with high heat transfer coefficient, then at the risk of galvanic corrosion, at the toxicity and last the cost price. In the following paragraphs, the characteristics of the tube are elaborated.

	λ (W/(m*K)	Price (eu/kg)
SILVER	417	850
COPPER	401	9
GOLD	317	63730
ALUMINUM	237	
BRONZE	1905	,50
BRASS	122	4,50
ZINC	116	
~~**NICKEL**~~	~~92~~	
IRON	79	
PLATINUM	72	30700
STEEL	50	
LEAD	35	
STAINLESS STEEL	15-27	1,15

(Figure 36: material choice of HEX tube)

HEAT TRANSFER COEFFICIENT

The tube in the tank must quickly transfer heat from the hot/warm drain water to the drinking water in the buffer. Therefore, a high heat transfer coefficient is desired for the material of the tube. Generally, metals are known to be good heat conductor. In Figure 36, metals with their heat transfer coefficient (λ) are listed from high to low.

DRINKING WATER SAFETY

According to Rijksoverheid (n.d.), the only metal listed in figure 36 that is toxic to the human body is Nickel. Therefore, this materials is excluded.

GALVANIC CORROSION

As mentioned in paragraph 6.1, the heat exchanging tube will be attached in the COMBI(+) buffer reservoir. Since the COMBI(+) reservoir is made of stainless steel (301), it is important to consider the risk of galvanic corrosion. Based on the table of Galvatech (2023), figure 36 shows in red the metals that are mentioned as low to no risk of galvanic corrosion. Still, some materials have a higher risk of galvanic corrosion over time than other materials. Nevertheless, there are methods and coatings to reduce the risk of galvanic corrosion.

PRICE

Based on the actual prices (as of April 2024) of the leftover material options listed in figure 36, copper, stainlesss steel, brass and bronze are significantly cheaper than materials like Silver, gold and platinum. Therefore, silver, gold and platinum are excluded as options for the HEX tube material. copper, stainless Steel and Brass all have a price per kg that is below 10 euros and all prices are in the same order of magnitude. Since copper is the best heat-conducting material available, and the difference in price between the other available materials is less significant than the difference in heat transfer coefficients, copper is chosen to be the material for the HEX tube.

UNCLOGGING AGENTS

Unclogging agents can be made of biological materials or of chemical materials. In case users use biological unclogging agents (e.g. baking soda and vinegar), there is no hazard in damaging the copper tube. Some chemical unclogging agents are also safe to use, but chemicals like sulfuric acid can be hazardous for copper. Still, there are enough options for users to safely unclog their copper tube HEX system.

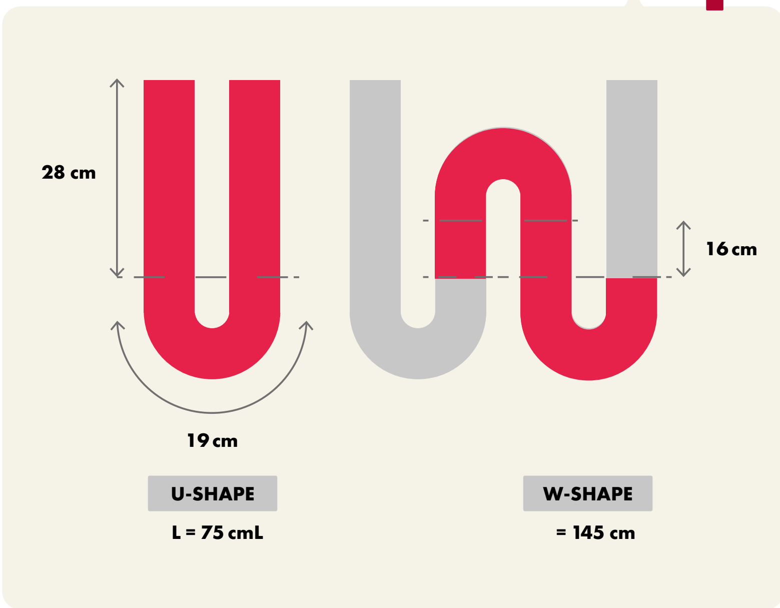
DIMENSIONS

Since the diameter of the copper tube has to be smaller than 40 mm so that the U&W-shaped tubes fit in the COMBI(+) reservoir, one standard copper tube diameter size smaller was used (35mm). The wall thickness is desired to have the smallest standard thickness possible, which is 1mm. However, for the prototype only 2mm wall thickness tubes were available in 35mm diameter (see next paragraph). Therefore the prototypes were tested with 2mm wall thickness. In figure 37, the difference in tube length between both prototypes are illustrated.

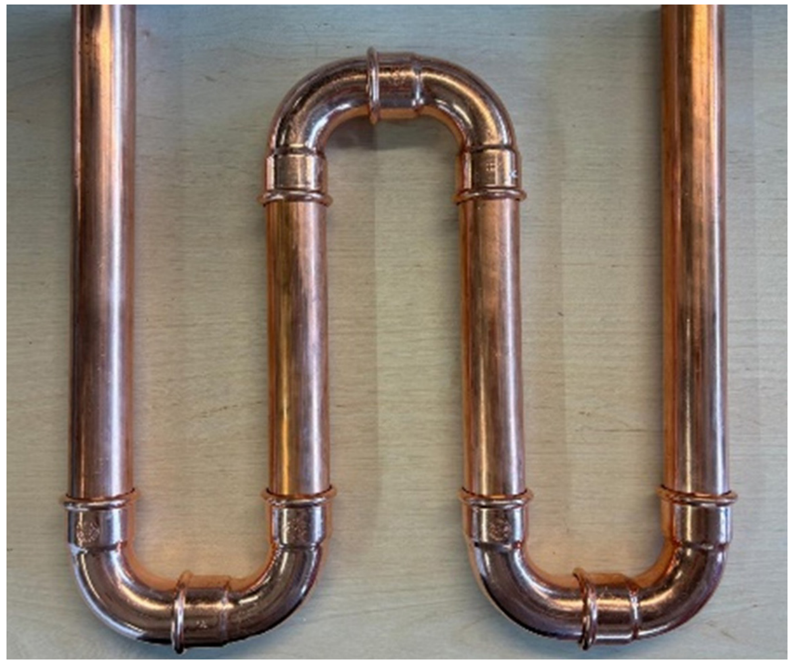
COST DIFFERENCE

After receiving input from a Quooker employee who is responsible for the purchasing logistics within the company, the price of the copper tube (figure 38) of both prototypes was estimated for when Quooker would sell a product with a bent tube as mentioned in the previous paragraph. For this estimation, it was assumed that Quooker buys the tube from an external company, that the wall thickness is 1 mm in reality and Quooker would bend the tubes in-house.

Based on a comprarison of resource cost prices, and based on the expertise and knowledge of the procurement specialist at Quooker, the expected purchasing price for the U-shaped prototype is €30,74 and for the W-shaped prototype the expected purchasing price is €59,45.



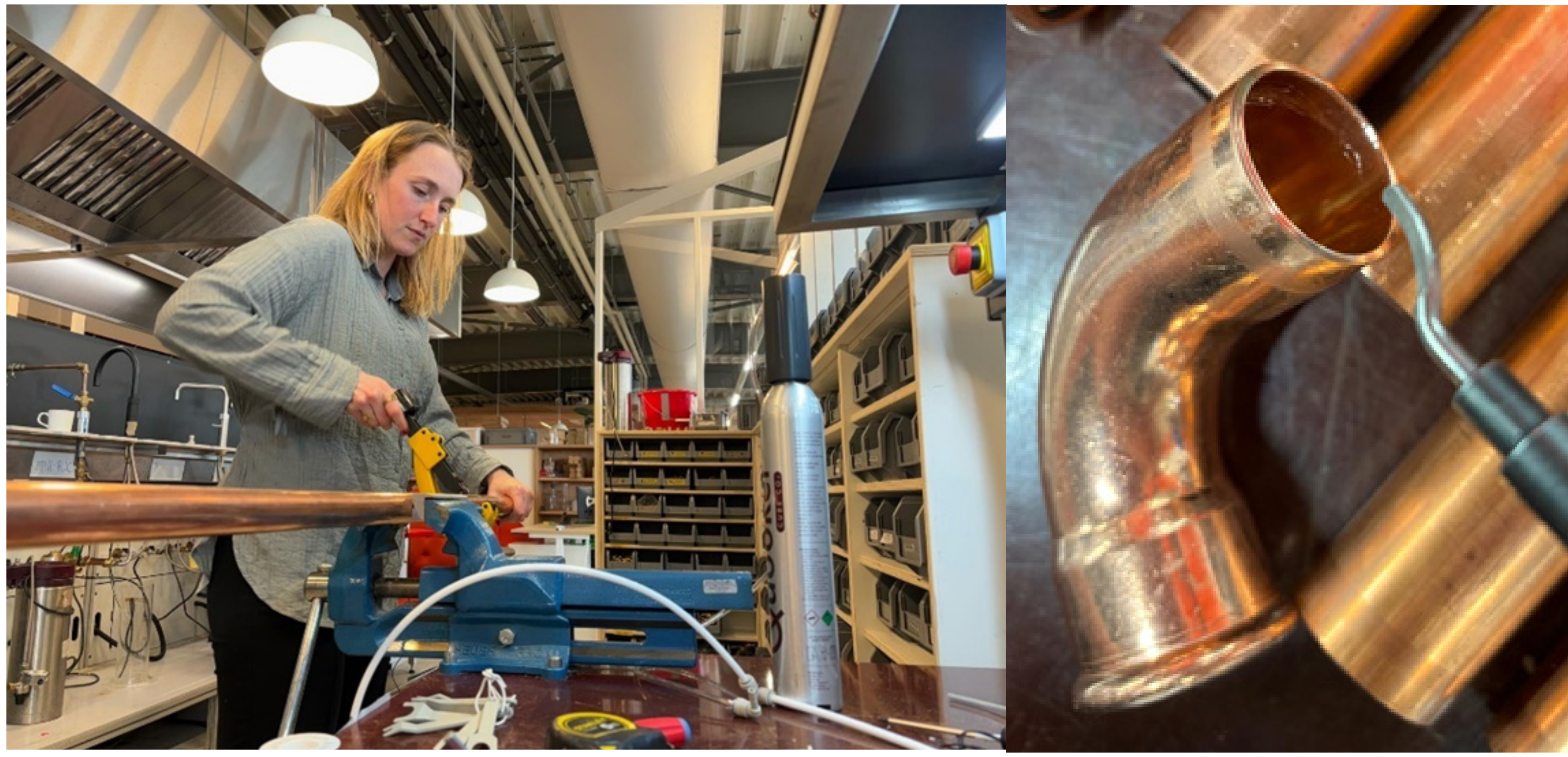
(Figure 37: tube length of U&W-shaped concepts)



(Figure 38: W-shaped copper tube before being pressed in reservoir fitting composition)

6.3. PROTOTYPE TESTING

In the final product, the copper tube would consist of one tube that is bent at the desired 180 degree angle. Since bending the tubes in the minimum bending radius requires additional machines or special tools a pre-bent 90-degree part was used for this prototyping. The bends and straight parts of the tube were cut to the desired length by a pipe cutter and the burrs were removed (figure 39). The bends were attached with a press jaw to a straight part of the copper tube (figure 40). The full prototyping process can be found in Appendix A10.



(Figure 39: tcutting the copper pipe and removing burrs)

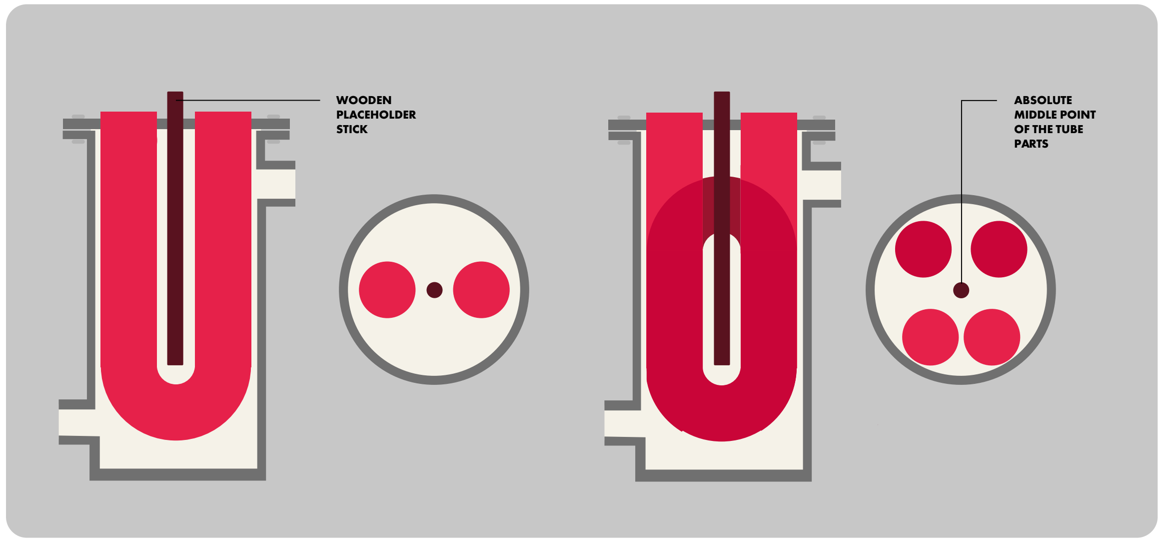
(Figure 40: attaching the parts by a press jaw)

After the HEX tube was ready, a PS layer was added as insulation (Figure 41). This layer was attached to the wooden lid of the buffer reservoir (Figure 42). The wood with counterbored holes for the HEX system was used to carry the weight of the HEX tube. The PVC tube was thermoformed with boiling water around the copper tube.

(Figure 41: W-shaped prototype with PS insulation & wire to carry the weight of the tube)

(Figure 42: U-shaped prototype with placeholder stick)

In the absolute middle point, where the distance between the placeholder stick and all the tube parts is equal, a placeholder stick was positioned (figure 43). This placeholder is meant to attach the thermocouples to test heat transfer.



(Figure 43: placement placeholder stick)

METHOD A/B TEST

Two concepts, U-shaped (A) & W-shaped (B) were evaluated for their efficiency in transferring heat from hot water to cold water through a HEX system over a 12-hour period, using two different scenarios. In the first A/B test, U-shaped and W-shaped prototypes were assessed by pouring 1.5 L of boiling water through the copper HEX tube. In the second A/B test, the prototypes were evaluated by sequentially pouring 1 L and then 2 x 2 L of boiling water through the copper tubes. The temperature at the inlet and outlet of the copper tube, as well as at four different water levels in the buffer reservoir, were monitored to determine the energy savings, and cost reduction, and carbon footprint of both prototypes. The calculation method outlined in Chapter 1 was used. Prior to the test, the copper tube and buffer reservoir were filled with cold tap water. It is noteworthy that the temperature of the cold water in this test was higher than typical for Dutch households, as the cold water supply originated from a buffer tank within the building. During this test, the cold water temperature was approximately 23 °C

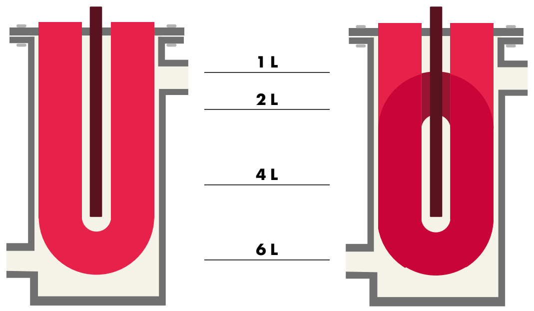
APPARATUS

- (1x) Boiling water proof measuring glass of 2L
- (1x) Calculator
- (1x) Pen
- (1x) Paper
- (1x) Tap water (+/- 23°C)
- (1x) Quooker tap & kettle for boiling water
- (1x) PicoLog TC-08
- (6x) thermocouple
- (1x) U-shaped prototype
- (1x) W-shaped prototype
- (1x) Duct tape roll
- (1x) Scissors
- (1x) Waterproof marker
- (1x) Glue
- (1x) PVC tube 40 mm
- (2x) PVC 90-degree bend 40 mm
- (1x) PVC adapter or funnel
- (1x) Drill
- (1x) Pico SDK 64 bit software
- (1x) Laptop that is capable of running picolog software
- (1x) Pair of heat proof gloves

PREPARATION

For tests 1 & 2, two prototypes (A&B) were created (paragraph 6.2). Both prototypes are identical, except for the copper tube HEX system. One prototype has a U-shaped copper tube as HEX system, and the other prototype has a W-shaped tube, both with the same diameter and wall thickness.

First, the difference in the volume of the copper tube of both prototypes was defined. This was calculated to be approximately 350 mL difference. Then, 8 L and 7.65 L of water were measured with the measuring can. The buffer reservoir for the U-shaped prototype was filled with 8 L of cold tap water and the W-shaped prototype with 7.65 L of water. Four depths within each tank were defined: 1L, 2L, 4L & 6L depth, through a calculation of the water volume distribution in the tank (figure 44). The position of these depths was marked on the wooden positioning stick in each prototype. After this, four thermocouples were threaded through the lid of the to-be-tested prototype and positioned with duct tape on the four different depths that were marked (figure 45).



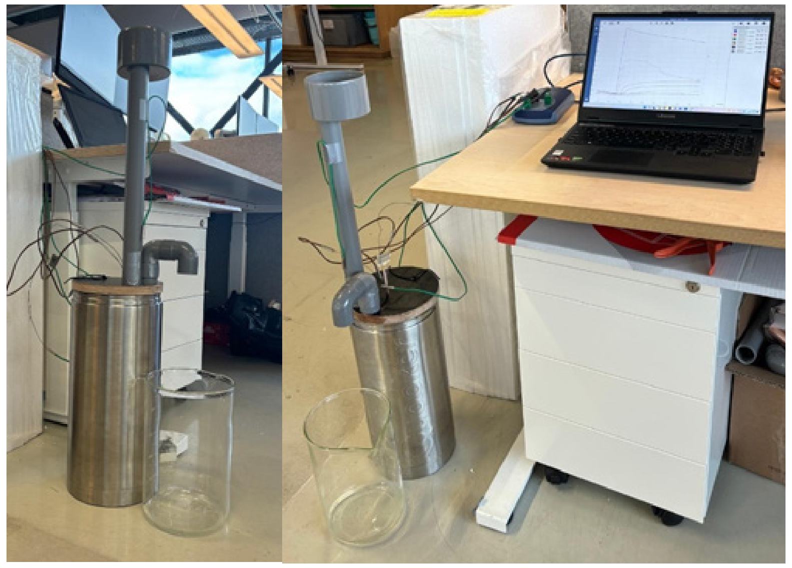
(Figure 44: different depths for thermocouples in buffer reservoir)

SET-UP

(Figure 45: U-shaped prototype with placeholder stick)

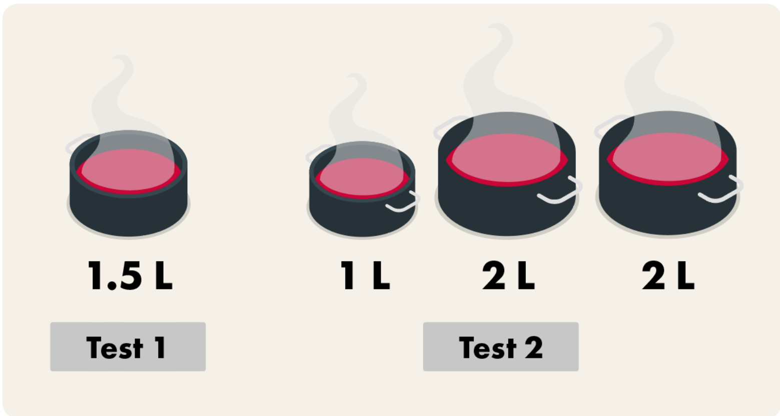
To ensure a good positioning of thermocouples at the inlet and outlet of the HEX system, a hole was drilled in the walls of the pvc tubes that are attached to the HEX system. Two thermocouples were threaded through the holes and attached in the center at the end of the bend and tube with glue and duct tape (Appendix A10). The two 90-degree PVC bends, of which one includes a thermocouple, are attached to the outlet of the copper tube.

In both prototypes, the HEX tube was filled with cold water to represent a realistic drain system. The ends of all 6 thermocouples were attached to the PicoLog device and to the laptop with PicoLog software to measure the temperature of the water over time.



(Figure 46: visualization of test set-up)

Both prototypes were placed indoors in the same environment and position (figure 46). The PicoLog software started measuring the temperature of all thermocouples (inlet, outlet, and buffer reservoir depths) for 12 hours, and started measuring a few minutes before pouring 1.5 L through the HEX system for test 1 (figure 47) . In test 2, the same test was conducted, but instead of 1x 1.5 L being poured through the HEX system, 1x 1L followed by 2x 2L boiling water were poured through the HEX systems of both prototypes.



(Figure 47: difference in boiling water poured through HEX system in test 1 and 2)

Pouring the boiling water was done with safety gloves to reduce burning risk. Test 1 was based on a scenario described in chapter 3. Test 2 was based on a scenario where most boiling water was poured through the sink (chapter 3). For test 2, the prototype had to be moved to another place, where other tests were conducted. In the results that are discussed later in this chapter, in test 2 a fluctuation in the values for the inlet and outlet of the copper tube were found. This may have been a result of someone replacing the prototype during the test.

DATA COLLECTION

The data collection of all 6 thermocouples was monitored through Picolog software. Picolog tracked the temperature of all 6 thermocouples for 12 hours long every 5 seconds. The data was saved in graphs (Appendix A12).

RESULTS

In this part, the results of A/B tests 1 & 2 are outlined. As mentioned earlier in this chapter, test 1 shows the effect of heat transfer on the water temperature at different depths in the buffer reservoir after pouring 1.5 L of boiling water through the HEX system (Figure 49 & 50). The graphs of test 1 show that the temperature difference of the peaks of the different water depths is max. 1 °C. The temperature peak of 1L depth is reached after approximately 20 minutes for both prototypes. However, the temperature peak of 2L of the U-shaped model is 10 minutes later than the U-shape. The same pattern is found for the 4 L peak but with a bigger time difference (1.5 h later). All measured water depths (1,2,4 & 6L) are at an equilibrium after approximately 7 hours (6L peak).

Blue line = inlet HEX system temperature

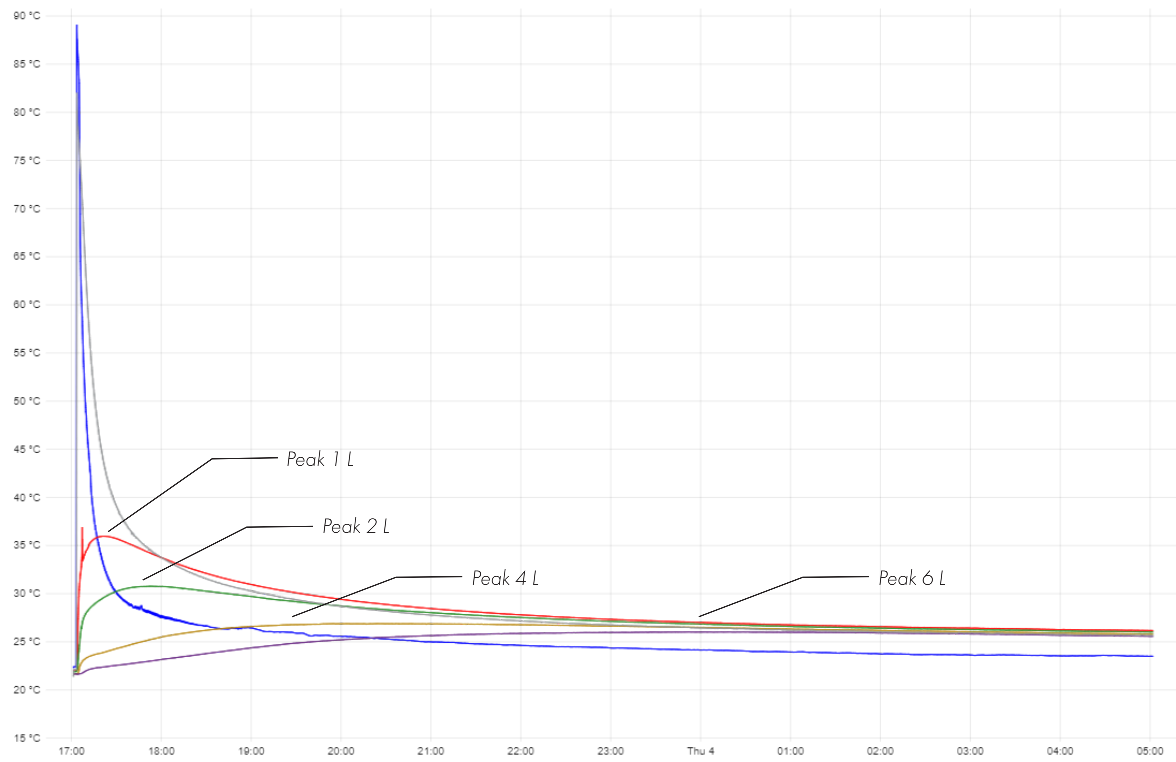
Grey line = outlet HEX system temperature

Red line = 1 L water depth in buffer reservoir (from water surface)

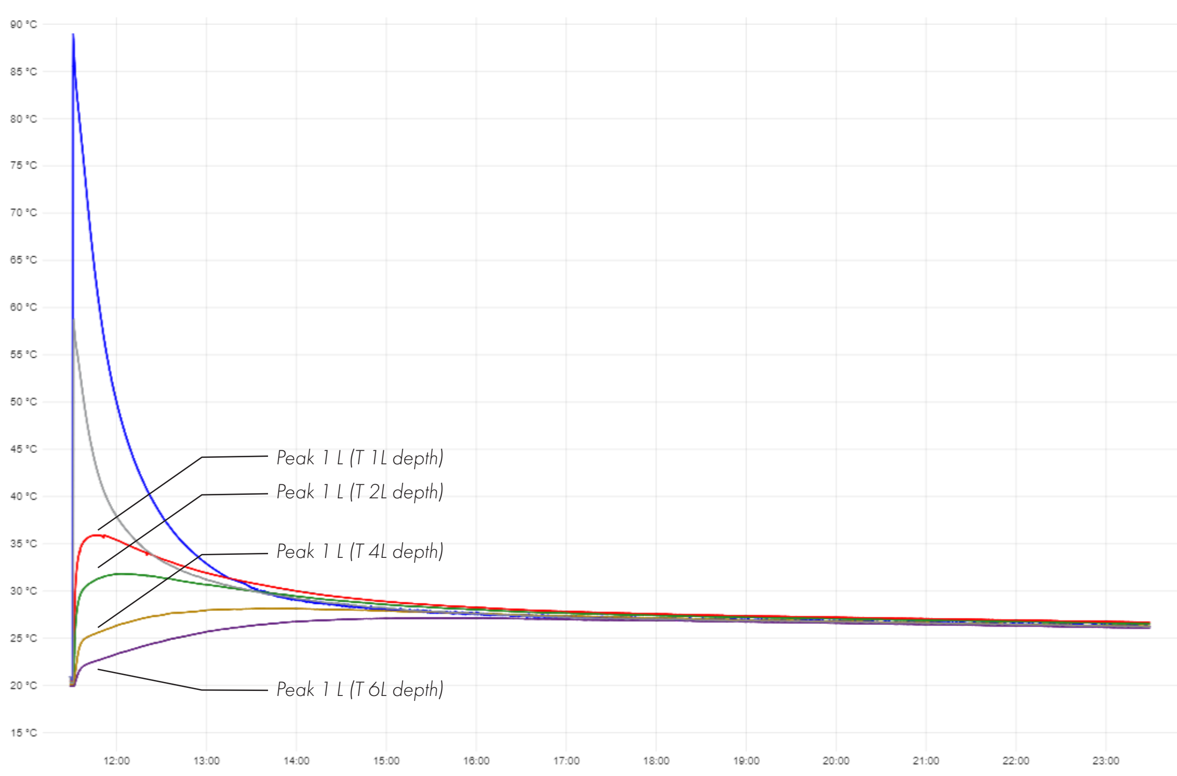
Green line = 2 L water depth in buffer reservoir (from water surface)

Brown line = 4 L water depth in buffer reservoir (from water surface)

Purple line = 6 L water depth in buffer reservoir (from water surface)



(Figure 49: outcomes A/B test 1 U-shaped model)



Blue line = inlet HEX system temperature

Grey line = outlet HEX system temperature

Red line = 1 L water depth in buffer reservoir (from water surface)

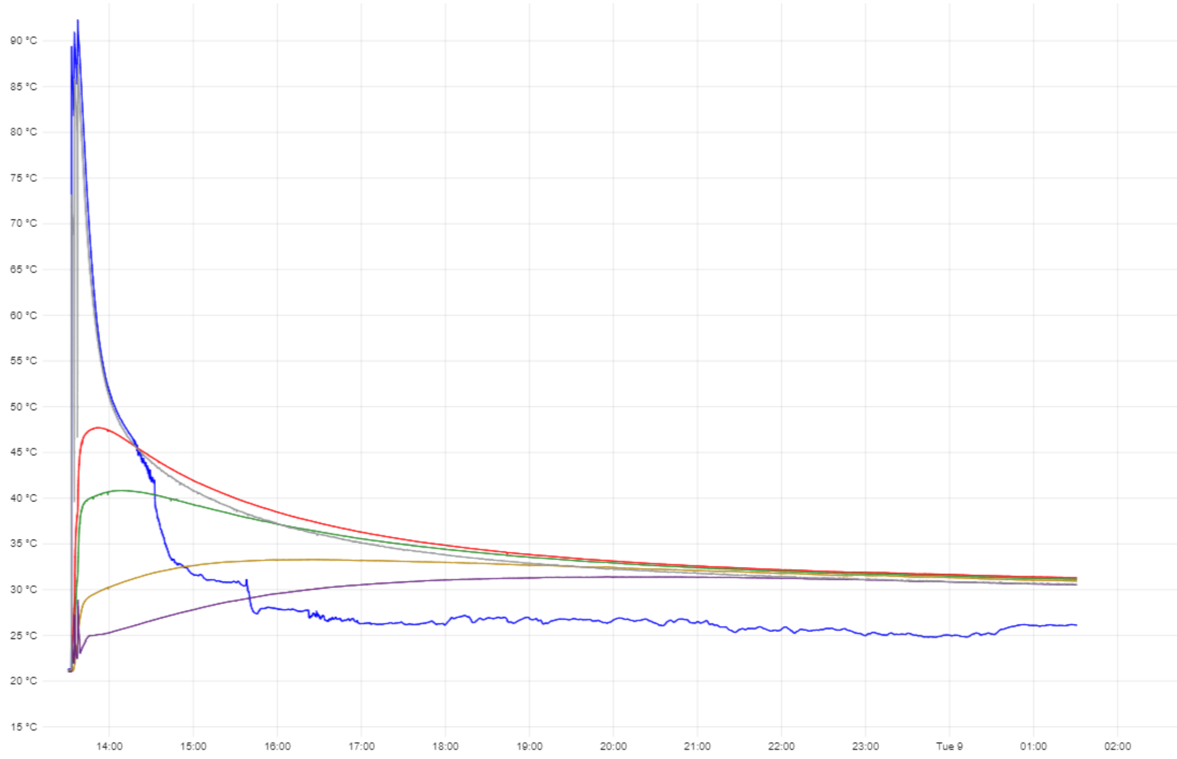
Green line = 2 L water depth in buffer reservoir (from water surface)

Brown line = 4 L water depth in buffer reservoir (from water surface)

Purple line = 6 L water depth in buffer reservoir (from water surface)

(Figure 50: outcomes test 1 W-shaped model)

On the 1 L peak moment, the temperature difference between the different layers of the water in the buffer reservoir is highest. Over time, the temperature difference decreases until an (almost) equilibrium.



Blue line = inlet HEX system temperature

Grey line = outlet HEX system temperature

Red line = 1 L water depth in buffer reservoir (from water surface)

Green line = 2 L water depth in buffer reservoir (from water surface)

Brown line = 4 L water depth in buffer reservoir (from water surface)

Purple line = 6 L water depth in buffer reservoir (from water surface)

(Figure 51: outcomes test 2 U-shaped model)

Blue line = inlet HEX system temperature

Grey line = outlet HEX system temperature

Red line = 1 L water depth in buffer reservoir (from water surface)

Green line = 2 L water depth in buffer reservoir (from water surface)

Brown line = 4 L water depth in buffer reservoir (from water surface)

Purple line = 6 L water depth in buffer reservoir (from water surface)

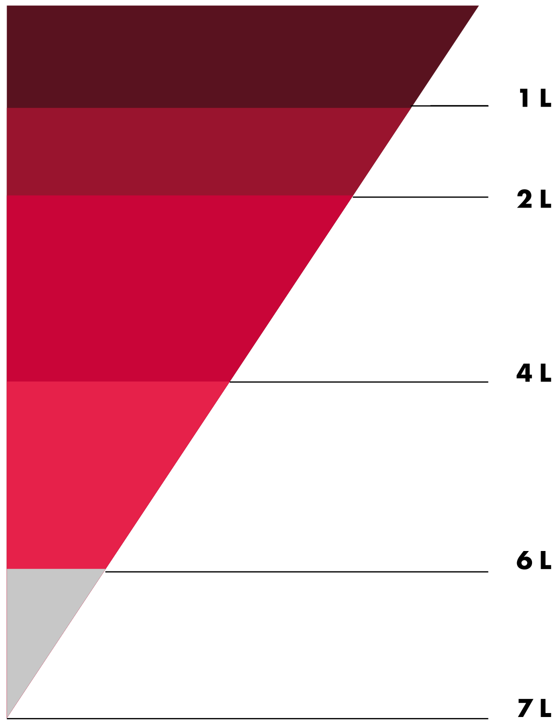
(Figure 52: outcomes test 2 W-shaped model)

Test 2 shows the effect of heat transfer on the water temperature at different depths in the buffer reservoir after pouring 1 L quickly followed by 2x 2 L of boiling water through the HEX system (Figure 51 & 52). The graphs of test 2 show that the temperature difference of the peaks of the different water depths is max. 3°C (at 6 L depth). On the 1 L peak, a temperature difference of 1 °C was found, on the 2 L peak there was no difference, and the 4 L and 6 L peaks had a 3°C temperature difference between both prototypes. Just as test 1, test 2 also shows a slower process of reaching the peak temperature at each depth for the U-shaped concept compared to the W-shaped concept. The time difference for 1 L was approximately 10 minutes, for 2 L this was 30 minutes, for 4 L 1 hour and for 6 L this was 2 hours time difference.

INTERPRETATION

Since the temperature difference between both prototypes of the different peaks in test 1 is max. 1°C, the difference between both concepts in this scenario is neglectable. However, at the 4 & 6 L peak, there is a significant peak time difference. As mentioned in Chapter 3, there is a wide variety in tapping/draining behavior between different users and on different days. In addition, the tapping/draining behavior of a user can be modified so that draining happens at the most beneficial moments. Therefore, the period difference of the different peaks between both prototypes is chosen to be less important than the captured heat difference in the water in the buffer reservoir.

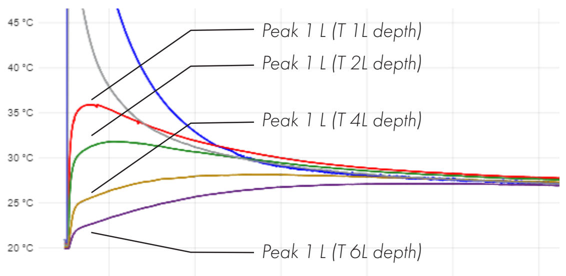
Test 2 shows a bigger difference in water temperature (3°C) at the different peaks. However, the distribution of the captured heat in the water in the buffer reservoir changes over time too. First, the warmest water can be found at the top of the buffer reservoir (Figure 53), but over time the water temperature gradually equals over time.



(Figure 53: water temperature at different depths in the buffer reservoi)

Since multiple use-scenarios showed that the dishwasher will likely be turned on after cooking and thus after draining boiling water, an average amount of 4.5 L (preheated) water will likely be requested by the dishwasher. Therefore, it is interesting to find the average temperature of the top 4 L and 6 L. An estimation for this was made by looking at the temperatures at different depths at different peaks (Appendix A11). The biggest temperature difference of the upper 4 & 6 L was found to be 3°C.

To get a better understanding of what a 3°C temperature difference for 4L and 6L water means, a calculation was made where 4L and 6L water were heated up to 3°C every day for 10 years (Appendix A12). The same calculation method as mentioned in Chapter 1 was used for this calculation. Heating up 4L of water every day for 10 years 3°C is €19 in cost difference. For 6 L this is €29.



Explanation of what is meant with different temperatures at one peak in the average water temperature of 4 L and 6 L calculation

PROTOTYPE CHOICE

As mentioned earlier, the purchasing price difference between the U-shaped and W-shaped of the copper tube is estimated at €28,71 (procurement engineer at Quooker International B.V.). According to Quooker, they sell products often with a price margin of 60 to 80 % above the purchasing price. Since heating up 6L of water every day for 10 years 3°C is €19 in cost difference, it is more cost-effective to choose for the U-shaped prototype. Additionally, choosing the U-shaped model results in less material use, which will decrease the carbon footprint of the model too. Furthermore, due to the smaller amount of bends and shorter tube length, the U-shaped model is less prone to fouling and clogging, and the cleanability and thus longevity of the product is higher.

REQUIREMENTS AND WISHES

1. Performance
1.1 It is required that the product consists of a thermal storage system (heat buffer)
1.2 It is required that the drinking water for consumption cannot meet the grey water in the system.
1.3 The heat storage system must be sensible and should transfer heat from water to water.
1.4 The heat recovery system must be able to measure the temperature of incoming grey water and the water in the buffer system.

2. Maintenance
2.1 The risk of fouling and clogging should be minimized.

3. Product costs
3.1 The production costs should be as low as possible.

4. Size and weight
4.1 The product should fit within the average size of a kitchen cabinet.

5. Esthetics, aesthetics, and finish
6.1 The products aesthetics should align with the other Quooker products.

6. Materials
6.1 The drinking water cannot be in contact with materials that are toxic for the human body for con sumption.
6.2 The product cannot contain heavy metals such as Cobalt, Mercury, Nickel or Lead.
6.3 The product cannot contain radioactive materials.
6.4 It is desired for the materials of the product to consist of recyclable materials.
6.5 The product parts that come in contact with water should not suffer from (galvanic) corrosion.
6.6 The HEX system should be able to handle natural/biological unclogging detergents.

7. Product life span
8.1 The product life span should be as long as possible.

8. Safety
8.1 The drinking water coming out of the system for consumption cannot contain materials that are toxic to the human body as drinking water.

9. Installation and use
9.1 The system should be leaking-proof.
9.2 The product should be installable by an installer.

10. Reuse and recycling
10.1 It is desired for the product parts to be parted as easily as possible for recycling.
10.2 It is desired for the product parts to be parted as well as possible so that the product can be repaired easily.

DELIVER

07

PRODUCT IN USE SCENARIO

In this chapter, a final 24- hour heat transfer test is conducted in a scenario where boiling water is drained and the dishwasher is turned on. The heat recovery is calculated in cost, kWh and carbon footprint. In addition, the final concept and additional research is presented. Finally, the final concept is evaluated on its viability, feasibility and desirability, and recommendations are elaborated.

KEY INSIGHTS

- Over a 10-year period, daily implementation of this scenario would result in energy savings of 678 kWh, cost savings of approximately €258, and a reduced carbon footprint of approximately 348 kg.

7.1. FINAL TEST

To get a better understanding of what the potential value of a heat recovering system in the kitchen context can be, a final test was conducted. This test was conducted to resemble use scenario where a relatively high heat recovery rate is expected when considering two actions that often occur in the kitchen conext: draining boiling water after cooking and turning on the dishwasher.

METHOD

For the final test, a plausible maximum scenario where three pans of boiling water were drained after cooking was used (Chapter 3). The dishwasher on high-intensity program was replicated and turned on at the most efficient moment after draining the three pans of boiling water (Chapter 6). In this final test, a dishwashers high-intensity program of 2.5 h with four cycles of washing was replicated with the given temperatures mentioned in Chapter 2. For this test it was assumed that there is no heat loss of the water that is used by the dishwasher during the cycles. Therefore, for this test it is assumed that the temperature of the water that is drained by the dishwasher is equal to the temperature the dishwasher heated the water up to initially to start the cycle. Additionally, it was assumed that first the water that resembles the dishwashers 'dirty' water is drained, after which directly new 'fresh' heated up water is requested.

After the extraction of each quantity of 4.5 L, fresh cold water is introduced into the buffer reservoir of the prototype via the inlet tube located at the reservoir's base. In addition, the extracted water is thoroughly mixed to measure the average water temperature. After resembling draining three pans of boiling water and all four dishwasher cycles, the data from the thermocouples is used to find the most efficient (peak) moment after the above named scenarios to tap 6 L of water. The water temperature results are used to calculate the energy, cost and carbon footprint savings after 10 years of this use scenario every day through the formula for heat capacity (1.1).

The test was conducted with an 'open system' prototype so that the prototype did not have to handle the average of 3 bar water pressure of the cold water net. Additionally, the water temperature at different water depths in the buffer reservoir (1L, 2L, 4L & 6L) were tracked over 24 hours of time. The temperature of the 'requested' dishwasher water from the buffer reservoir was measured, collected and analysed.

APPARATUS

- (2x) Boiling water proof measuring glass/bucket of at least 4.5L
- (1x) Calculator
- (1x) Pen
- (1x) Paper
- (1x) Tap water (+/- 23 °C)
- (1x) Quooker tap & kettle for boiling water
- (1x) PicoLog TC-08
- (6x) thermocouple
- (1x) thermometer
- (1x) U-shaped prototype
- (1x) Duct tape roll
- (1x) Scissors
- (1x) Water- and heat proof glue
- (1x) Water- and heat proof kit
- (1x) Drill
- (1x) Stainless steel tube inlet 415 mm (diameter 10 mm)
- (1x) Stainless steel tube outlet 115 mm (diameter 10 mm)
- (2x) Push-in fitting diameter 10mm
- (3x) LLDPE tube (diameter 10 mm)
- (1x) Needle valve
- (1x) Screw-in coupling to push-in fitting for cold water net
- (1x) Pico SDK 64 bit software
- (1x) Laptop that is capable of running picolog software
- (1x) Pair of heat proof gloves

PREPARATION

For the final test, the U-shaped prototype of the A/B test mentioned in Chapter 6 was used. This prototype was modified so that it has an cold water inlet- and outlet and so that the prototype can be attached to the cold water net through an open system (Appendix A13).

Additionally, a bucket was filled with 4.5 L of water. At this water level, a duct tape mark was added to the inner side of the bucket. The outlet tube of the buffer reservoir was placed in this bucket. The cold water inlet of the buffer reservoir is attached to the cold water net by a screw-on to push-in fitting. To reduce the water flow of the cold water before it enters the buffer reservoir, a needle valve was added in the middle of the LLDPE inlet tube.

Then, a time schedule was made for pouring preheated water through the copper tubes of the prototype and for tapping 'requested' water from the outlet of the buffer reservoir so that the dishwashers' resembled high intensity programme was started at the optimum moment of 35 minutes after draining the three pans of boiling water (Table 1).

Time	Action
13:00	Fill copper tube & buffer tank until the maximum water level with cold tap water
13:09	Prepare a measuring glass with 1 L boiling water
13:10	Pour 1 L boiling water through the copper tube
13:11	Prepare a measuring glass with 2 L boiling water
13:12	Pour 2 L boiling water through the copper tube
13:13	Prepare a measuring glass with 2 L boiling water
13:14	Pour 2 L boiling water through the copper tube
13:45	Tap 4.5L of water out of the buffer reservoir and measure temperature of this 4.5 L water
14:15	Prepare a measuring glass of 4.5 L water of 45 °C
14:20	Pour 4.5 L water of 45 °C through the copper tube
14:23	Tap 4.5 L of water out of the buffer reservoir and measure temperature of this 4.5 L water
14:53	Prepare a measuring glass of 4.5 L water of 58 °C
14:48	Pour 4.5 L water of 58 °C through the copper tube
15:01	Tap 4.5 L of water out of the buffer reservoir and measure temperature of this 4.5 L water
15:31	Prepare a measuring glass of 4.5 L water of 47 °C
15:36	Pour 4.5 L water of 47 °C through the copper tube
15:39	Tap 4.5 L of water out of the buffer reservoir and measure temperature of this 4.5 L water
16:09	Prepare a measuring glass of 4.5 L water of 64 °C
16:14	Pour 4.5 L water of 64 °C through the copper tube

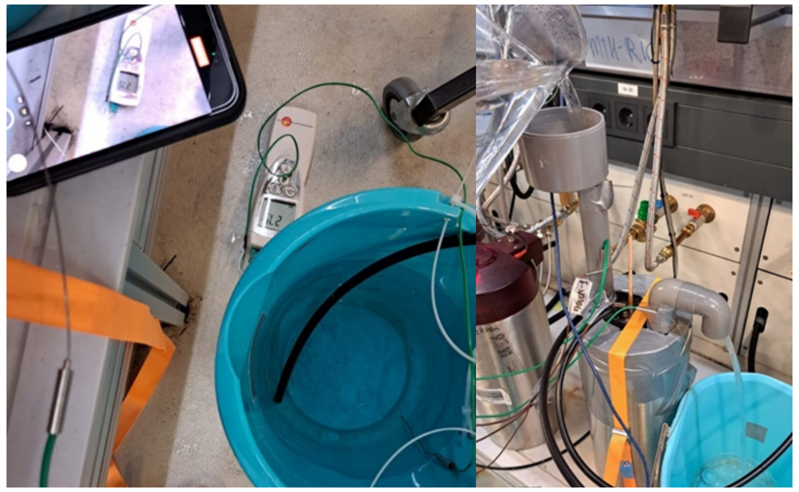
(Figure 54: time table final test)

SET-UP

The test set-up was positioned in a stable environment. The cold water temperature was higher than in regular Dutch households since the cold water supply at the test set-up was coming from a buffer tank in the building. In this test the cold water was approximately 23 °C. During the test, the PicoLog software measured the temperature over 24 hours time of all 6 thermocouples attached to the PicoLogger.

The water that had to be poured through the copper tube was brought to desired temperature and volume by mixing boiling water and cold water in a measuring glass and by measuring the temperature of the water with a thermometer.

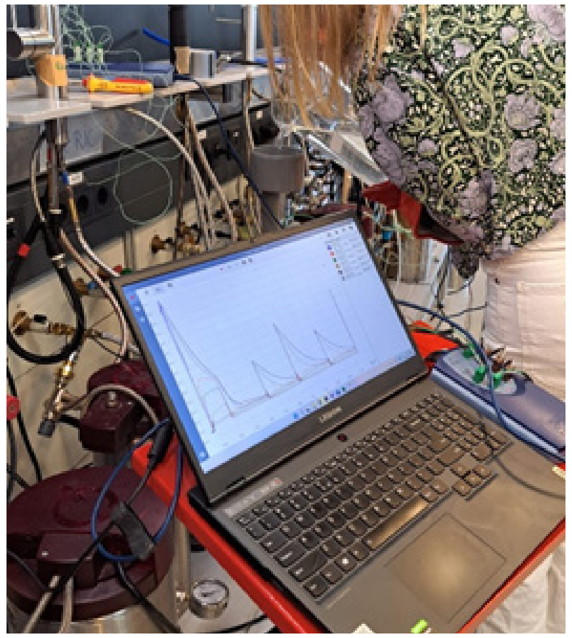
A calibrated bucket marked at 4.5 L was placed at the outlet of the buffer reservoir to facilitate the extraction of 4.5 L of water from the buffer reservoir. The temperature of the water coming out of the outlet of the buffer reservoir was mixed directly after taping and measured in temperature with a thermometer (figure 55). A bucket was positioned beneath the outlet of the copper tube to collect the discharged water (figure 55). Pouring hot water was done using safety gloves.



(Figure 55: test set-up & measuring water from outlet buffer reservoir)

DATA COLLECTION

The data collection of all 6 thermocouples was monitored through Picolog software. Picolog tracked the temperature of all 6 thermocouples for 24 hours long every 5 seconds. The data was saved in graphs. Additionally, the temperature of the water coming from the outlet of the buffer reservoir is measured by a thermometer. The results are written down in a table and used for further calculations (Appendix A14).



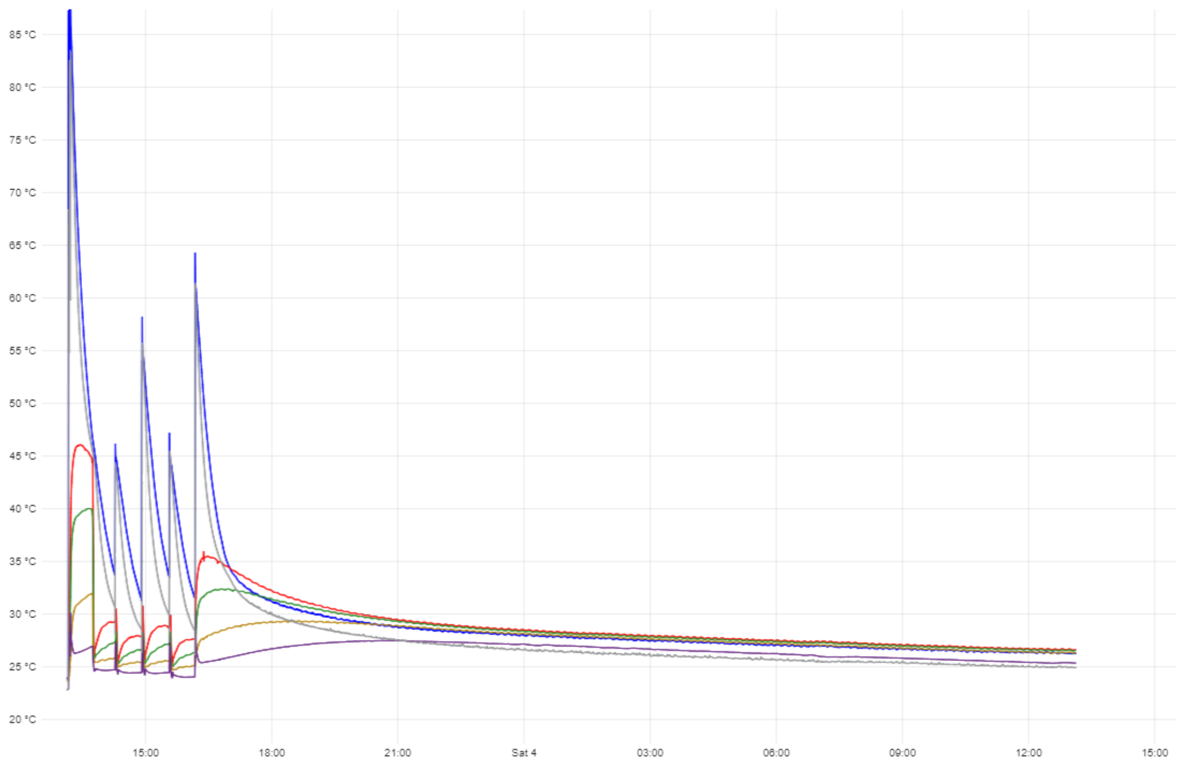
(Figure 56: data collection during test by PicoLog software)

RESULTS

Tap	T water (°C)	ΔT start (°C)
#1	36.3	8.7
#2	27.5	4.5
#3	28.2	5.2
#4	27.3	4.3
#5	29.2	6.2

(Figure 57: measured water temperature of 4 cycles of tapping 4.5 L requested water)

This section presents the outcomes of the final test. As previously mentioned in this chapter, the initial temperature (T start) of the water in both the buffer reservoir and the copper tube is approximately 23 °C. Figure 57 shows the water temperatures recorded during the four dishwasher cycles (cycles #1-4). Cycle #5 illustrates the calculated maximum average temperature of 6 L of water following the simulated usage scenario described earlier in this chapter. The calculations in appendix A15 indicate that the optimal time to draw 6 L of water is at the peak temperature of 2 L, approximately 40 minutes after the last dishwasher cycle is drained through the prototype's copper tube (Figure 58 & 59). ΔT start represents the temperature difference between T start and T water (figure 57). This difference, ΔT start, indicates the increase in temperature and consequently the energy saved by the prototype
The data presented in figure 57 were used in the calculations to determine the energy reduction achieved by using the prototype over a ten-year period, assuming daily implementation of this use



Blue line = inlet HEX system temperature

Grey line = outlet HEX system temperature

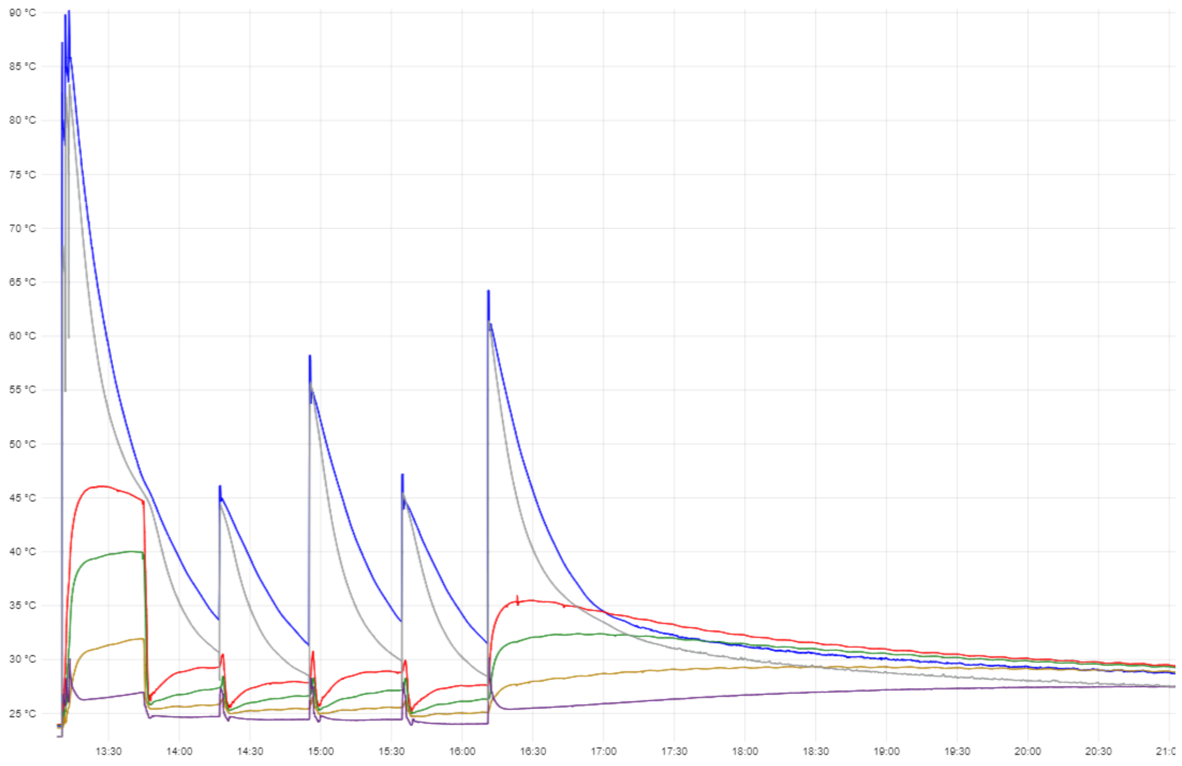
Red line = 1 L water depth in buffer reservoir (from water surface)

Green line = 2 L water depth in buffer reservoir (from water surface)

Brown line = 4 L water depth in buffer reservoir (from water surface)

Purple line = 6 L water depth in buffer reservoir (from water surface)

(Figure 58: data final test 24 h)



(Figure 59: data final test 24 h zoomed in)

Calculations indicate that conducting the use scenario of the final test every day over a 10 year time period, the energy reduction is 678 kWh. In cost reduction this is approximately €258 and the reduced carbon footprint is approximately 348 kg (Appendix A15).

DELIVER

08

FINAL CONCEPT

In this chapter, an overview of the final product characteristics are elaborated, including the estimated cost price. In addition, ideal usage of the system is described, and the projects complexity is outlined. Next to that, important rules and regulations are highlighted, and the net sustainability is evaluated. Furthermore, the market segmentation and an implementation strategy is discussed, after which a stakeholder validation is outlined. Finally, the project impact for other contexts is elaborated on.

KEY INSIGHTS

- The final concept includes a pressure reducing valve (QRV) already present in Quooker kettles, a stainless steel cover to prevent galvanic corrosion, and an electronic solenoid valve with a custom-made thermometer.
- The total production cost is estimated at €83.40, with a retail price of €500, resulting in an approximate 20-year payback period based on current energy and resource prices.
- Potential cost savings through material reuse and reduced initial investment are noted, but the impact of added components like the copper tube on cost and carbon footprint needs further evaluation.
- Optimal performance depends on user behavior, such as draining hot water before cooler water and avoiding simultaneous draining and tapping. Efficiency varies with seasonal temperature changes, being more effective in winter.
- Compliance with drinking water safety regulations necessitates adding a check valve and possibly a double wall to separate greywater from drinking water to prevent contamination and minimize legionella risks.
- The system could reduce CO_2 emissions by 348 kg over 10 years, potentially achieving a net-zero carbon footprint for the combined Quooker system.
- Attracting eco-conscious customers could be challenging due to their typically lower water use behaviors, necessitating alternative selling points like shorter return on investment or aesthetics.
- The primary target market is Quooker's existing customer base, mainly consisting of baby boomers, Gen X and millennials. However, future customers, illennials and Generation Z, showing higher willingness to pay for sustainable products.
- Marketing as an add-on to existing Quooker systems can align with Quookers current business model.
- Collaboration with educational institutions could raise awareness and interest in sustainability among future customers.

8.1. PRODUCT CHARACTERISTICS

In figure 60, the final concept is shown in different views. In reality the buffer reservoir is closed (figure 61).

1. Cap
   a. Q button
   b. Q button electronics
   c. Cap shell & electronics
   d. PCB
   e. Cover electronics
   f. Screws (5x)
   g. PS insulation layer cap
2. PVC outlet/inlet pipes (2x)
3. Solenoid electronic valve with temperature sensor
4. Water outlet buffer reservoir
5. Cold water inlet buffer reservoir
   g. Cold water inlet tube
6. Temperature sensor
7. PVC connection tubes (2x)
8. Connection ring cap
9. PS insulation layer
10. Nuts (1 lx)
11. Lid
12. Stainless steel cover
13. Rubber ring
14. Copper HEX tube
15. Buffer reservoir

(Figure 61: exploded view of final concept)

Additionally, an exploded view with the materials of the final concept is displayed (figure 61).

For the final concept to work in context, a pressure reducing valve (QRV) is needed to cover the fluctuation in water pressure of the water net per household or context. Since a QRV is already a part of Quookers kettles, this part does not have to be added to the parts of this final concept and is thus not used in the cost price calculation (Appendix A16). The final concept contains a stainless steel cover so that the copper tube does not get in contact with other metals that can increase the risk of galvanic corrosion (figure 61). As mentioned in the previous paragraph, a QRV is added to the Quooker system, which ensures a maximum of 3 bar water pressure on the system. Therefore, under the stainless steel lid, a rubber ring is attached to make the buffer reservoir water proof under 3 bar pressure. The lid is used for closing off the buffer reservoir. On the lid, an insulation layer is added to prevent heat loss through the lid.

An electronic solenoid valve with a thermometer inside is attached to the drain water inlet of the final concept (figure 61). A solenoid valve with an integrated thermometer is a part that is not yet available on the market. Therefore, this should be a part that is custom made for this application. Together with a procurement expert at Quooker the cost price of such a solenoid valve was estimated (Appendix A16). The thermometer at the inlet is necessary to compare the incoming water temperature in the copper HEX tube to the water temperature of the water in the buffer reservoir. In the situation where the incoming drainwater is colder than the water in the buffer reservoir, the drainwater is diverted away from the HEX tube into the drain system. However, ss a result of the heat transfer from warm drain water to colder water in the buffer reservoir, a more accurate temperature comparison could be achieved by changing the position of the thermometer in the buffer reservoir from the reservoir into the copper tube. However, adding a thermometer in the copper tube can increase the chance of fouling and clogging and may make the system more complex and could potentially increase the cost price of the product. Therefore, this thermometer is positioned in the buffer reservoir, a position that still gives valuable information for the HEX to work sufficiently. However, the best height of the thermometer in the buffer reservoir is yet to be determined.

Since the COMBI(+) kettle of Quooker has similar features to the final concept, materials of the COMBI(+) can be reused. This results in a product that aesthetically fits within the product line of Quooker, which is beneficial since the final concept is meant to work with Quookers' kettles.

Additionally, the reuse of materials enlarges the chance for Quooker to start circular initiatives like refurbishment or recycling. The stainless steel reservoir that is reused, for example, consists of only one material, ideal for recycling and refurbishment.

The main difference of the final concept with the COMBI(+) is that the final prototype does not include an inner stainless steel flask. Therefore, the buffer reservoir needs an additional rim to screw the lid, rubber ring and stainless steel cover on.

The cap of the final concept is elevated with the diameter of the PVC inlet- and outlet tubes so that these can enter and exit the cap. In the exploded view of figure 61, the current Quooker COMBI cap is shown. However, the current cap still works on 230 V. In consultation with an embedded engineer at Quooker International B.V., it was concluded that it is likely that the cap of this final prototype can probably communicate the temperature differences measured by both thermometers to the kettle and drive the solenoid valve. In this case, the solenoid valve should be a latching valve, to be able to work on 12 V. In addition, it is also likely that a button is not necessary, and that the PCB can be smaller than in the current cap. Therefore, in consultation with an embedded engineer and a procurement expert at Quooker, a cost price was estimated for a cap that would be able to use the power of the kettle and is able to communicate with the kettle. This 'new' cap price is included in the cost price table in appendix A16.

Additionally, the lid, rubber ring and stainless steel cover are increased in diameter and the holes for the water filter and electronics in the design of the COMBI(+) are removed. Since e.g. these electronic parts, the stainless steel reservoir flask and the water filter are not necessary for the final prototype, those can be removed from the parts list as well and thus will the cost price and carbon footprint reduced. However, the copper tube is added, which has a significant negative impact on the cost price, initial investment and will have an affect on the carbon footprint. The net impact of the changes should still be evaluated through an LCA of the final concept (see recommendations).

In terms of investment, the initial investment costs for Quooker on parts like the buffer reservoir, the inlet- and outlet of the water are reduced as a result of reuse of materials and machines.

In consultation with a procurement expert at Quooker, the total production cost price of the final concept was estimated to be €83,40 (Appendix A16). In case Quooker would like to sell this product with their profit margin (x6), the retail price is estimated to be €500. This means that the payback time in the situation where the final test would be an everyday use scenario is approximately 20 years (Chapter 6). Still, the payback time is not only dependent on the use scenario, but also on the energy and resource prices. However, predicting future fluctuations in energy and resource prices is challenging due to their dependence on various factors, such as sustainability policies, technological innovations, supply and demand dynamics, and geopolitical considerations. Consequently, it is essential to frequently monitor developments in energy and resource prices.

8.2. IDEAL USE & COMPLEXITY

Defining an ideal use scenario for the heat recovery system is challenging due to the variability in kitchen tapping and draining behaviors, which can differ daily and from person to person. Generally, the system performs better when more water is drained and when the drained water is warmer. However, several key usage aspects should be considered:

- Drained water with a lower temperature than the water in the buffer reservoir is diverted away by the solenoid valve. Therefore, it is beneficial to drain water with a higher temperature than the water temperature in the buffer system. For example, in case a user first drains boiling water and then quickly after rinsing their dishes with medium warm water, the heat of the medium warm water is not used for heat recovery since the water in the system is warmer.

- The system functions optimally when there is no simultaneous flow of draining and tapping water. As the ideal tapping time after draining warm/hot est use scenario can determine the optimal moment to turn on the dishwasher after draining boiling water (approximately 35 minutes).
- Since the cold water net temperature is lower in winter than in summer, it is likely that using this heat recovery system in winter will be more efficient than in summer.

These aspects are dependent on the use behaviour of customers. Therefore, the user can influence the systems' efficiency by changing their tapping and draining water behaviour in the kitchen. Customers can be advised to e.g. turn on their dishwasher after 35 minutes after cooking. Another example is that users can be advised to not leave the tap open to create a non-simultaneaus tapping/draining flow. An example of this in doing the dishes through a hand wash is first filling their pans and turning off the tap and then rinse the pan with this water and drain the water in the pan and repeat during the dishes.
Since the heat recovery system functions as a 'hot fill' for the kettle and the dishwasher, the users with only a cold water supply in the kitchen at home, and thus the users that use their Quooker kettle for the supply of warm water, make best use of this heat recovery system. Therefore, users with a COMBI reservoir are likely to have most benefit of the heat recovery system, followed by users with a COMBI+ reservoir.

8.3. GREYWATER & DRINKING WATER

Since the heat recovery system is using greywater and still standing water, some hazards occur. In this paragraph, hazards and rules and regulations around drinking water safety are outlined and evaluated on the effect on the final concepts specifications.

RULES & REGULATIONS

According to a product compliance specialist at Quooker, just as with other devices that are attached to the drinking water net, it is important to add a check valve to the system (NEN-EN 1717). A check valve ensures that ditch-water is not flowing back into the fresh water net.
The product compliance specialist also stated that rules and regulations indicate that greywater in the kitchen context is categorized as category 5. This type of category are fluids that represent a serious health hazard by containing a concentration of pathogenic organisms. Therefore, there is a chance that a double wall is needed to separate grey water from fresh drinking water.
Some shower heat recovery system manufacturers design the HEX tubes with holes in the wall in the tube length (Recoup, 2022). These holes can create a double layered wall. Creating these holes in the copper tube of the final concept, can increase the cost price. To what extent the cost price of the copper tube is increased still has to be researched.

LEGIONELLA

One of the reasons there are strict rules and regulations around drinking water quality is the risk of legionella growth. Legionella grows best in still standing water with a watertemperature between 25 and 55 °C. According to a legionella expert at KDWS (2024), the risk of legionella problems in this heat recovery system is limited. He stated that legionella amongst other bacteria will get killed when the drinking water coming from the HEX system passes the Quooker kettle and therefore will form no hazard for the drinking water coming out of the Quooker kettle. He mentioned that legionella mainly forms a serious health hazard when the condensation drops are breathed in by a user. In principle, this does not happen with intended use of the dishwasher. However, in case a user would open the dishwasher during a washing programme, there is a risk of inhaling water drops from the dishwasher. Nevertheless, the expert mentioned that he thinks the risk is minimum, since a dishwasher is often used on a daily basis and that this risk also counts for the stillstanding water in a dishwasher after use.

8.4. NET SUSTAINABILITY

The calculations of the final test illustrate that a potential CO_2 eq reduction after 10 years use is (Chapter 7) is 348 kg CO_2 eq.

Since the final concept reuses key parts of the COMBI(+) reservoir, it is assumed that the carbon footprint of the production & construction process stages of the COMBI(+) reservoir are in the same value range. Some crucial parts of the COMBI(+) reservoir are namely reused, some (electronic) parts and the tap are removed from the original kettle and others, like the copper tube, are added. Nevertheless, an in depth LCA on the final product should be considered to provide a more precise carbon footprint value.

Production & construction process stages consist of:

- Raw material supply
- Transport
- Manufacturing
- Transport gate to site
- Assembly

Quooker (n.d.), states that the carbon footprint of the production & construction process stages of a simple Quooker tap & COMBI(+) combination is calculated to be 141 kg CO_2 eq. This means that the calculated carbon footprint reduction after 10 years use (final test) is around 2.5 times higher than the carbon footprint of its production & construction process stages.

For the PRO3 and a simple Quooker tap, the carbon footprint of the production & construction process stages is 119 kg CO_2 eq. Therefore, there is a chance that everyday use of the current prototype for 10 years can bring the net carbon footprint of the production & construction of a tap, a COMBI(+) kettle and the final concept to zero. Consequently, this can attract eco-conscious customers (Chapter 3).

However, the scenario that is tested in the final test is based on a potential maximum use scenario. The dishwasher, for example, is replicated at high intensity programme. It is likely that an eco-conscious user, that could be attracted to the idea of bringing the carbon footprint of the production and construction progress stages to net zero emissons, have more eco-conscious (warm) water use behaviour. Likely, these customers use their dishwasher on eco-programme, resulting in less heat recovery and thus decreasing the chance of bringing the production of their whole Quooker system to net zero.

Additionally, the conducted interviews showed that users that think they make sustainable choices, name having e.g. solar panels at home as an eco-conscious choice. Since solar panels mainly provide energy at daytime, kettle or dishwasher use at daytime can be covered by the energy that is generated by the solarpanels. In case the dishwasher is used at these times, and the user has solar panels, the heat recovery system will not reduce the energy consumption of a dishwasher, and of the Quooker kettle.

Therefore, a contradictory situation unravels: the customer group that is likely to be more attracted to an eco-conscious add-on to the Quooker system, is likely to have less sustainable 'benefit' of such a system. For customers to truly make a difference, the system would work best for the customers that care less about the environment and thus show that in their more excessive warm water use. To attract this group, other unique selling points like a short return of investment or aesthetics should be reached.

8.5. MARKET SEGMENTATION & IMPLEMENTATION STRATEGY

Quookers' business model is centered around its flagship product: the Quooker kettle. Since Quooker started off as a company that sells instant boiling water, taps and kettles are sold as an integrated package. If a customer desires chilled or sparkling water, this option is available only if they already own a Quooker tap and kettle, or if they purchase a Quooker tap and kettle as a set. Only accessories, such as the soap dispenser, are sold as standalone products.

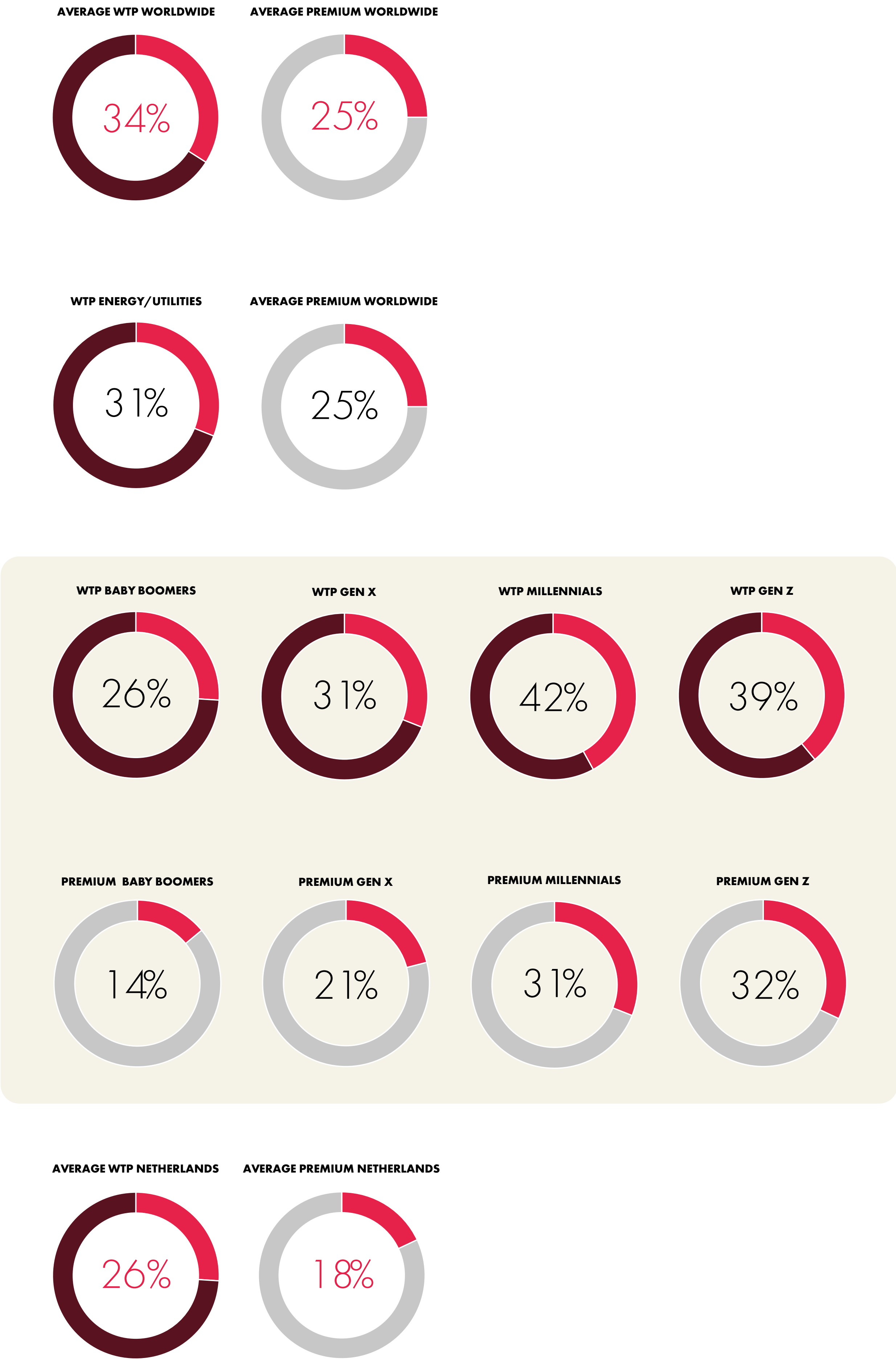
To integrate a heat recovery solution in Quookers' current business model, it would likely be marketed as an add-on to the Quooker kettle and tap. This approach allows Quooker to increase revenue from its current customer base. Furthermore, by introducing a product that could potentially reduce the net carbon footprint of the kettle, tap (COMBI(+) or PRO3), and heat recovery solution to zero, Quooker can enhance its sustainable brand image. This strategy could attract sustainability-conscious customers, thereby not only increasing revenue but also expanding the customer base.

Given that Quooker employs over 250 individuals, it must comply with the Corporate Sustainability Reporting Directive (CSRD) and the European Energy Efficiency Directive (EED) (Frijters, 2021). These regulations require large companies to report their sustainability efforts and objectives. Incorporating a heat recovery system in Quooker's product lineup could improve its standing in relation to these regulatory requirements.

Additionally, a study by Simon-Kucher & Partners (2021), involving 10,281 global respondents, assessed their willingness to pay (WTP) for sustainable goods and services. On average, 34% of global respondents are willing to pay a premium for sustainable goods and services, with an average premium of 25%. Within specific industries, 31% of respondents are willing to pay more for energy and utilities, with an average premium of 25% (Figure 62).

The study also reveals generational differences in WTP for sustainable products. Millennials exhibit the highest willingness to pay, followed by Generation Z. Interestingly, Generation Z respondents willing to pay a premium are prepared to pay the highest premium (32%), closely followed by millennials (31%) (Figure XX). As Quooker targets high-end market segments, its current primary customers are baby boomers, Generation X, and partially millennials. However, in the coming years, the target demographic is expected to shift towards millennials and Generation Z. Consequently, the desire for sustainable goods/services and willingness to pay for a sustainable good or service for Quookers customers is expected to increase in the future.

In the Netherlands, 26% of respondents, on average, are willing to pay a premium for sustainable goods. The average sustainability premium a Dutch respondent is willing to pay is 18%. As younger generations become the predominant customer base, an increase in WTP for sustainable products is expected, aligning well with Quooker's evolving business model.



(Figure 62: WTP & premium for sustainable goods/services (Simon-Kucher & partners, 2021)

Marketing the heat recovery solution as an add-on to existing Quooker systems to achieve net-zero production emissions can be interpreted as customers paying a premium on the initial price for a more sustainable Quooker system. The retail price of the most affordable tap and kettle combination (Flex/Fusion+PRO3) is €1,295, while the combination with the COMBI(+) is priced at €1,595 (Quooker, n.d.). Thus, the additional amount Dutch customers are willing to pay for a sustainable system, referred to as the 'premium' (figure 62) is currently €233 for the PRO3 system and €287 for the COMBI(+) system. Globally, the average 'premium' price is higher: the willingness to pay (WTP) premium is €324 for the PRO3 and €399 for the COMBI(+). For future customers, specifically millennials and Generation Z, the average premium would be €407 for the PRO3 combination and €502 for the COMBI(+) combination. This indicates that future customers are willing to pay nearly double the amount for a heat recovery system compared to baby boomers.

However, it is crucial to consider that customers are only willing to pay more for a sustainable product if they genuinely desire the product (Chapter 3). One of the key factors of the desirability of a product is the level of return of investment. Since after 10 years everyday use of the use scenario described in the final test results is €258, the return of investment time is approximately 20 years. Given that the average lifespan of a kitchen is between 15 and 20 years, and that the return of investment time of e.g. solar panels is around eight years, this return of investment period is long and thus likely not to be short enough to be desirable to users (Interieurbouw, 2024)(Milieu Centraal, n.d.).

One potential strategy for Quooker is to reduce its profit margin to enhance the product's desirability. However, Quooker indicates that while it is feasible to lower the retail price by approximately 10-15%, such a reduction would not be sufficient to achieve a return on investment within a ten-year timeframe.
Another strategy to reduce the return on investment time is to use grants for sustainability initiatives. In the Netherlands, grants are available for similar sustainable products, such as shower heat recovery systems. The Dutch government classifies a heat recovery shower as an additional measure (RVO, 2020). It is likely that a heat recovery system for Quooker would receive a similar classification if grants become available in the future. To qualify for a grant in this category, two 'regular sustainable measures' such as floor or wall insulation must first be implemented. The grant for a shower heat recovery system ranges from 16% to 23% of the original price, including renovation costs (Subsidieverbouwing, n.d.). However, since there are specific efficiency requirements, it remains uncertain whether a grant will be available for a kitchen heat recovery system.

Since there is a chance that the strategies named above are not feasible, the desirability of the heat recovery system for a business-to-consumer (B2C) market with the current design and customer base is expected to be low. To implement such a system in the short term, Quooker could focus on businesses. Certain sectors that frequently drain hot water or use dishwashers, such as cafeterias or restaurants, could be potential target groups. In this scenario, Quooker would market their heat recovery solution through business-to-business (B2B) channels.

Furthermore, Quooker could investigate the potential applicability of this heat recovery solution in other industries, such as the medical field. For instance, certain medical equipment is cleaned using medical washing machines that require a disinfection cycle with temperatures of at least 90 °C (O'Connor & Armstrong, 2014).

As previously discussed, millennials and Generation Z represent the future customer base for Quooker. Conversations within the company have indicated that if a heat recovery system becomes more cost-efficient, Quooker would consider its implementation following the completion of current sustainability projects. In preparation for selling to these generations, it is crucial to understand their desires and preferences. Equally important is educating them about the significance of sustainability.

Raising brand awareness among these generations is essential to prepare future customers for sustainable innovations and to establish Quooker as a prominent brand. Quooker could begin targeting millennials by engaging with universities, providing information about sustainability and heat recovery, and promoting their brand. Additionally, Quooker could collaborate with high schools to reach Generation Z, thereby fostering early awareness and interest in sustainability and the Quooker brand.

8.6. STAKEHOLDER VALIDATION

To better understand user opinions on the final concept, short validation conversations were held with two participants. These participants were presented with final render images, a brief explanation of the working principles, and the outcomes regarding sustainability and cost efficiency. Additionally, they were shown another Quooker COMBI kettle and informed that the final product would have the same dimensions, except for a height increase of approximately 4 cm. The interviewees were then asked for their opinions on the final design. Within Quooker, opinions were also solicited regarding the potential introduction of this final concept into Quooker's product portfolio.

The interviews revealed that not all kitchen cabinets have sufficient space for such a system (Figure 63). One participant was unconcerned with the payback time and appreciated the idea of making the Quooker system carbon-neutral. She expressed interest in acquiring the system after renovating her kitchen and was curious about future efficiency improvements.

Another participant found the space claim acceptable and appreciated that the product maintained the same aesthetic style as the Quooker COMBI kettle. This participant did state that the initial cost was too high still and that hopefully future efficiency improvements will result in a shorter return of investment period so that the concept is desirable.
Quooker expressed potential interest in this solution, in case there is room for optimization of cost efficiency and after the completion of ongoing sustainability projects at Quooker.

(Figure 63: User validation interviews with 2 interviewees)

8.7. PROJECT IMPACT

Sustainability is a shared goal among users, governmental bodies, and companies. Therefore, there is a growing demand for sustainable solutions, including heat recovery systems. While existing heat exchange systems prioritize high efficiency, certain applications may benefit from the gradual transfer of heat between materials. Current heat recovery systems capable of handling thicker or contaminated liquids are often complex and expensive. The proposed heat recovery solution aims to minimize costs and carbon footprint, specifically designed for use with greywater, which may make it suitable for various contexts. Further research is required to determine the applicability of this solution in different scenarios. The following unique selling points of this product are highlighted:

1. The product is capable of handling greywater and potentially other contaminated liquids.

2. Optimal performance is achieved when there is a non-simultaneous flow between the two liquids involved in the heat transfer. Therefore, a delay between water requests, such as after draining, is advantageous. Multiple devices can be interconnected to facilitate heat recovery from one device to another.

3. The system can be optimized when specific amounts of liquids are drained and requested at set intervals.

Consequently, contexts that involve multiple warm water devices operating and draining at different times could benefit from this heat recovery solution. Examples include bathrooms with showers and washing machines, or medical industries where dishwashers operate at higher temperatures with contaminated water due to disinfection cycles. Additionally, research could explore the implementation of an integrated kitchen ecosystem, where not only the dishwasher and Quooker kettle are connected, but also residual heat from appliances such as refrigerators or ovens.

This heat recovery system represents a significant advancement towards a more sustainable future, a vision that requires collective effort and innovation.

DELIVER

09

CONCLUSION & EVALUATION

Since the aim of this project is to create a proof of concept to evaluate the value of implementing a heat recovery system in the kitchen context, the final concept is evaluated in this chapter. The concept is evaluated on its feasibility, viability, and desirability. Finally, conclusions are drawn, and recommendations for further research are discussed.

9.1. FEASIBILITY

The heat recovery concept for Quooker has demonstrated technical feasibility. Existing heat exchangers, the proof of principle through a prototype, and the tests conducted for this research indicate that heat can be effectively recovered from warm drain water using a copper tube. User behavior tests, contextual analysis, and technological research confirm that this solution is suitable for the kitchen environment.
Furthermore, the reuse of existing product parts, electronics, and machinery currently used by Quooker enhances the feasibility and viability of implementing and producing this concept. Although the development of a solenoid valve with an integrated thermometer is required specifically for this application, it leverages existing technologies. Therefore, the development of this particular solenoid valve is not anticipated to encounter significant feasibility challenges.
Potential risks, including fouling/clogging, galvanic corrosion, and material toxicity, have been addressed, and relevant water quality regulations have been evaluated and adressed. Nevertheless, the design of this heat recovery system requires additional research in different fields to potentially increase the system's efficiency. In paragraph 9.4, the recommendations and the next steps for Quooker are elaborated.

9.2. DESIRABILITY

The desirability of this concept has been primarily assessed through contextual research, user behavior tests, and validation interviews. The findings suggest that customer desire for a product is influenced by several factors, including aesthetics, product maintenance, retail price, sustainability, and return on investment. The aesthetics were considered by incorporating the existing design style of Quooker kettles. Product maintenance, the carbon footprint of production, and cost were minimized by selecting a HEX system that is both simplistic and has a low risk of fouling and clogging.

Despite efforts to reduce the production cost, the initial retail price remains relatively high. While the concept has been developed with sustainability in mind, and proves to be net sustainable in production in the researched use scenario, the efficiency of the current final design results in a longer return on investment compared to other household heat recovery systems. Therefore, improving the system's efficiency whilst considering the increased cost and carbon footprint by doing so is crucial to enhancing its overall desirability to users.

Additionally, the tapping and draining behaviour of users is taken into account in the design of this concept by creating a HEX system that allows users to have a suitable 'ideal' moment of turning on the dishwasher after cooking. Users do not have to change their current kitchen use behaviour to an extend that it wil have a high impact on their everyday behaviour. However, future research may reveal other adjustments in users' tapping and draining practices could further enhance the system's efficiency.
User feedback on the final concept was generally positive, with participants appreciating its sustainability and aesthetic alignment with the existing Quooker COMBI kettle. However, there were concerns about the system's space requirements in kitchen cabinets and its initial cost. One participant was particularly interested in the system's carbon-neutral potential and future efficiency improvements, while the other hoped for a shorter return on investment period. After further development of the prototype, additional interviews should be conducted to validate the concept.

9.3. VIABILITY

To align with Quooker's current business model, the heat recovery solution is anticipated to be marketed as an add-on to Quooker's flagship product, the kettle. Consequently, this final concept is likely to be perceived as a desirable product, driven by factors such as return on investment, aesthetics, cost, and sustainability. Given that the tested scenario has a long payback period for the initial investment and Quooker's limited ability to reduce their profit margin, this product is currently not viable for short-term business-to-consumer (B2C) commerce.

However, there is potential for marketing this product in the short term to a niche market, specifically through business-to-business (B2B) commerce, where a higher use rate of the heat recovery solution is expected. Quooker is expected to have relatively low initial investment costs for implementing this system in the short term due to the reuse of existing product parts and machinery.

The current customer base of Quooker primarily consists of baby boomers, Generation X, and partially millennials. Over time, this demographic will shift towards millennials and Generation Z, whose preferences and interests are more oriented towards sustainable products and a higher willingness to invest in such products. Therefore, targeting B2C sales could become more appealing for Quooker in the future. It is essential to understand and anticipate the desires and preferences of these future customers and to educate them about the importance of sustainability.

Additionally, future opportunities for grants aimed at sustainable innovation or products could enhance the product's viability. These factors collectively suggest that while the heat recovery system may not be immediately viable for the broader consumer market, it holds significant potential for niche markets and future consumer bases that prioritize sustainability.

9.4. CONCLUSION

The findings of this research highlight that implementing a heat recovery solution in the kitchen could have significant benefits. To be more specific, it could save 678 kWh, and therefore reduce costs by €258, and decrease carbon footprint emissions by 348 kg after 10 years of daily use. All, whilst the projected retail price for this system is estimated at €500.

When comparing the reduction in carbon footprint with the footprint associated with the production and construction stages of the COMBI kettle, tap, and the heat recovery system, it becomes apparent that the net carbon footprint would reach zero after less than 10 years of daily use.

However, a comparison between the estimated retail price and the calculated cost savings suggests that the return on investment would occur after approximately 20 years of daily use, which is a long period. Therefore, further research is necessary to optimize the system's efficiency. It is important to note that this calculation is based on a single, potential usage scenario. In practice, tapping and draining behaviors vary significantly among users, adding complexity to the project. Therefore, additional research is required to explore various use scenarios and guide users toward optimal tapping behavior to enhance the system efficiency.

The effectiveness of the heat recovery system increases with the amount and temperature of water drained. However, this contradicts the principles of 'sustainable' water usage. Eco-conscious users, who are likely to be interested in such a system, may consequently experience fewer benefits from both sustainability and economic perspectives.

Given that the primary goal of this project was to create a proof of concept, further research is essential to fully assess the system's feasibility, viability, and desirability (see next paragraph for recommendations). Additionally, future changes in energy prices, product costs, and regulatory environments may have a significant impact the evaluation of the system's overall value.

Finally, as the shared goal on achieving net-zero emissions by 2050 raises, sustainable awareness is also growing. Therefore, further research should be conducted into various contexts where warm wastewater is drained, or where different appliances that use warm greywater are connected to the same piping system. This would help determine the broader applicability of the heat recovery solution, potentially extending its benefits beyond the kitchen environment.

9.5. RECOMMENDATIONS

Research direction:

Investigate the potential value of using a water filter system with a more efficient existing heat exchanging system to mitigate the risk of fouling and clogging of the system.

Enhancing Heat Exchange Efficiency:

Investigate the impact of adding extra plates to the heat exchanger, which could potentially accelerate heat transfer from the drain water to the water in the buffer reservoir. This improvement could be particularly beneficial during nearly simultaneous water tapping and draining moments, such as between dishwasher cycles.

Explore the use of alternative materials like stainless steel for the heat exchanger plates, given the high cost of copper.

Optimizing Buffer Tank Volume and Configuration:
Determine the optimal volume for the buffer tank and the ideal configuration for the copper tubing. This requires extensive user research to understand tapping and draining behaviors in the kitchen. A larger sample size is needed to draw significant conclusions about these behaviors.
Incorporate seasonal variations in cold water inlet temperatures (summer and winter) into long-term efficiency tests.

Important Factors:

Evaluate critical aspects such as cleanability, toxicity, longevity, sustainability, and cost efficiency when assessing potential improvements. These factors should be considered when adding extra plates, adjusting the buffer reservoir volume, and configuring the copper tube dimensions.

Investigating Inlet Turbulence Effects:

Research the impact of turbulence and water velocity at the buffer reservoir inlet on the heat transfer rate.

User Behavior and System Configuration:

Conduct more extensive user research to better understand the most effective system configuration. Evaluate whether using simultaneous water streams or the current buffer tank design yields better performance. This depends on the volume and temperature of both the drained and incoming water.

Life Cycle Assessment:

Perform an in-depth life cycle assessment (LCA) of the heat recovery system to obtain a more precise estimate of its carbon footprint.

Double-Walled Copper Tubing:

Investigate the cost implications and heat transfer efficiency of using double-walled instead of single-walled copper tubing for the heat exchanger.

Additional Application Contexts:

Explore the implementation of this heat recovery system in other contexts beyond the kitchen. This could help Quooker expand its market scope and application areas.

9.6. DISCUSSION & LIMITATIONS

The final test provided an indication of a potential maximum use scenario, focusing only on draining pans with boiling water after cooking and operating the dishwasher on a high-intensity program. This narrow scope excludes other common use scenarios, limiting the comprehensiveness of the conclusions drawn. For example, doing dishes by hand was not included in the analysis, suggesting that the actual heat recovery potential in the kitchen is likely higher than indicated by the final test. Similarly, the cold tap water used in the final test had a higher temperature than average summer and winter tap water temperatures, which also suggests that in reality the heat recovery rate could be higher. Nevertheless, the calculations were based on a maximum potential use scenario and the 'ideal' tapping moment. In reality it is likely that some days the heat recovery system will be used less than tested in this research. To achieve a more accurate and complete understanding, it is important to investigate different use scenarios by identifying patterns in tapping and draining behavior on a larger scale.

In addition, the final test calculations did not account for fouling and clogging over time, which can significantly influence the system's efficiency. Future research should consider these factors to assess their impact on the system's long-term performance. These additional studies should examine diverse user habits and environmental conditions to provide a more accurate assessment of the heat recovery system's efficiency. By doing so, the research can account for variations in daily kitchen activities, leading to a more robust evaluation of the system's potential benefits.

Furthermore, the carbon footprint of producing the heat recovery solution for Quooker was a rough estimation. Conducting an in-depth Life Cycle Assessment (LCA) could provide a more precise measurement of the carbon footprint of the final concept, ensuring a more accurate evaluation of its environmental impact.

By addressing these discussion points, future research can offer a more comprehensive evaluation of the heat recovery system's feasibility, efficiency, and overall value in the kitchen context for Quooker.

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APPENDIX

A

A0: PROJECT BRIEF

DESIGN FOR our future

TU Delft

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)

In light of the global initiative to achieve net-zero CO2 emissions by 2050, energy efficiency and the prevention of energy loss are becoming more important [1]. This goal is a collective responsibility for governments, municipalities, corporations, and individuals. The implementation of heat recovery systems could be a potential solution to work towards this shared goal. Heat recovery systems reduce energy consumption, resulting in sustainable and economic value [2]. Recognizing the potential impact, Quooker aims toinvestigate the feasibility of harnessing residual heat from water for integration into their boiling water Quooker system [3].

For the evaluation of the viability of heat recovery for Quooker, an exploration of diverse heat recovery systems is desired with merits, and drawbacks. Furthermore, conducting an analysis, which involves the development of a functional prototype, of the most promising system can help to evaluate the sustainable and economic value of such a system. This investigation not only supports Quooker's goals of innovation, sustainability efforts, and brand positioning but also aligns with the shared goal of achieving net-zero CO2 emissions by 2050.

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[3]: Graduation opportunity by Quooker

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:

Create a Proof of concept to evaluate the value of implementing a heat recovery system in the kitchen context.

I aim to research in which ways rest warmth of water can be reused and integrated into the current Quooker system. The outcome will be a (physical) proof of concept that also includes calculations and tests about the energy efficiency.

In the process of creating the final 'proof of concept' I am planning on using the triple diamond method, which allows me to explore different systems and possible solutions. Next to that, I plan to do research on already existing heat recovery systems and their applications. I would like to explore the kitchen (sink, tap, cabinet and drain) context and relevant technologies by doing desk research and by e.g. conducting interviews. I would like to prototype and iterate to eventually come to a final concept prototype for my proof of concept. I will substantiate my design choices with e.g. desk research, (user)tests and calculations.

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting, mid-term evaluation meeting, green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	5 dec 2023
Mid-term evaluation	21 feb 2024
Green light meeting	12 apr 2024
Graduation ceremony	21 mei 2024

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

My main ambition during this project is that I hope to further develop my embodiment skills. During my masters IPD I feel like I have developed quite some technical skills, however, I feel like I mostly had tasks that were focused on aesthetics or technical/user tests. Therefore I feel like I still want to develop my prototyping and thus practical technical skills.

During my work at studio Ninaber I saw the production of Secrid and learned a lot about the logistics, product parts and got in touch with some of the machines in the workshop. I really enjoyed working there and learned a lot from my boss, that is an inspiring designer to me. I liked that everything was built there in house, such as is done at Quooker and I liked how a lot of prototypes were made to test aspects of the factory. Here I realised that I would like to work more practical, think along in the bigger picture and that I like having contact with stakeholders. Since I like to have contact with stakeholders, I would like to learn how to better take the lead in managing multiple stakeholders and a project at the same time. I organised a study trip last year (Flight Case), where I have practiced my stakeholder contact skills already for a while. I aim to continue on practicing this skill.

Additionally, I would like to learn how to present my progress and concepts in a convincing way. I find presenting often challenging and I hope to learn how to be more confident during my presentations and to create a convincing story.

A1: CALCULATIONS AVAILABLE ENERGY, COST AND CO2

Total energy drained from hot Quooker water

```
> restart;
> #Lifespan [years]
  Lifespan := 10;
  #Water [L]
  Waterperday := 1.5;
  #Temperature [°C]
  TQuooker := 110;
  Ttap := 10;
  Tdrain := 80;
  #specific heat water [J/°C/kg]
  c := 4180;
  days := 365;
  CO2kgeqperKWh := 0.513;
                                        Lifespan := 10
                                        Waterperday := 1.5
                                        TQuooker := 110
                                        Ttap := 10
                                        Tdrain := 80
                                        c := 4180
                                        days := 365
                                        CO2kgeqperKWh := 0.513
> Totalwaterusage := Lifespan·days·Waterperday;
  Totalwaterusage;
                                        Totalwaterusage := 5475.0
                                        5475.0
> Qquooker := Totalwaterusage·c·(Tdrain − Ttap);
                                        Qquooker := 1.601985000 × 10^9
> KWhQuooker := 1/(3.6·10^6)·Qquooker;
  CostQuooker := KWhQuooker·0.38;
                                        KWhQuooker := 444.9958334
                                        CostQuooker := 169.0984167
> CarbonfootprintQuooker := CO2kgeqperKWh·KWhQuooker;
                                        CarbonfootprintQuooker := 228.2828625
```

miro

Total energy drained from dishwasher lowest energy program

```
> #Based on average of use of the dishwasher 1x per day per household (parents with kids)
> #Lifespan [years]
  Lifespan := 10;
  #Water [L]
  Waterpercycle := 4.5;
  #Temperature [°C]
  Tprewashlow := 19;
  Tmainwashlow := 41;
  Tfirstrinsinglow := 32;
  Tsecondrinsinglow := 45;
  Ttap := 10;
  #specific heat water [J/°C/kg]
  c := 4180;
  days := 365;
                                        Lifespan := 10
                                        Waterpercycle := 4.5
                                        Tprewashlow := 19
                                        Tmainwashlow := 41
                                        Tfirstrinsinglow := 32
                                        Tsecondrinsinglow := 45
                                        Ttap := 10
                                        c := 4180
                                        days := 365
> Totalwaterusage := Lifespan·days·Waterpercycle;
  Totalwaterusage;
                                        Totalwaterusage := 16425.0
                                        16425.0
> Qprewashlow := Totalwaterusage·c·(Tprewashlow − Ttap);
                                        Qprewashlow := 6.179085000 × 10^8
```

```
                                             Qprewashlow := 6.179085000 × 10^8
> Qmainwashlow := Totalwaterusage·c·(Tmainwashlow − Ttap);
                                             Qmainwashlow := 2.128351500 × 10^9
> Qfirstrinsinglow := Totalwaterusage·c·(Tfirstrinsinglow − Ttap);
                                             Qfirstrinsinglow := 1.510443000 × 10^9
> Qsecondrinsinglow := Totalwaterusage·c·(Tsecondrinsinglow − Ttap);
                                             Qsecondrinsinglow := 2.402977500 × 10^9
> Qlow := Qprewashlow + Qmainwashlow + Qfirstrinsinglow + Qsecondrinsinglow;
                                             Qlow := 6.659680500 × 10^9
> KWhlow := 1/(3.6·10^6)·Qlow;
                                             KWhlow := 1849.911250
> Costlow := KWhlow·0.38;
                                             Costlow := 702.9662750
> Carbonfootprintlow := CO2kgeqperKWh·KWhlow;
                                             Carbonfootprintlow := 949.0044712
```

Total energy drained from dishwasher highest energy program

```
> #Based on average of use of the dishwasher 1x per day per household (parents with kids)
>
> #Lifespan [years]
  Lifespan := 10;
  #Water [L]
  Waterpercycle := 4.5;
  #Temperature [°C]
  Tprewash := 45;
  Tmainwash := 58;
  Tfirstrinsing := 47;
  Tsecondrinsing := 64;
  Ttap := 10;
  #specific heat water [J/°C/kg]
  c := 4180;
  days := 365;
                                             Lifespan := 10
                                             Waterpercycle := 4.5
                                             Tprewash := 45
                                             Tmainwash := 58
                                             Tfirstrinsing := 47
                                             Tsecondrinsing := 64
                                             Ttap := 10
                                             c := 4180
                                             days := 365
> Totalwaterusage := Lifespan·days·Waterpercycle;
  Totalwaterusage;
                                             Totalwaterusage := 16425.0
                                             16425.0
> Qprewashhigh := Totalwaterusage·c·(Tprewash − Ttap);
                                             Qprewashhigh := 2.402977500 × 10^9
> Qmainwashhigh := Totalwaterusage·c·(Tmainwash − Ttap);
                                             Qmainwashhigh := 3.295512000 × 10^9
> Qfirstrinsinghigh := Totalwaterusage·c·(Tfirstrinsing − Ttap);
                                             Qfirstrinsinghigh := 2.540290500 × 10^9
> Qsecondrinsinghigh := Totalwaterusage·c·(Tsecondrinsing − Ttap);
                                             Qsecondrinsinghigh := 3.707451000 × 10^9
> Qhigh := Qprewashhigh + Qmainwashhigh + Qfirstrinsinghigh + Qsecondrinsinghigh;
                                             Qhigh := 1.194623100 × 10^10
> KWhhigh := 1/(3.6·10^6)·Qhigh;
                                             KWhhigh := 3318.397500
> Costhigh := KWhhigh·0.38;
                                             Costhigh := 1260.991050
> Carbonfootprinthigh := KWhhigh·CO2kgeqperKWh;
                                             Carbonfootprinthigh := 1702.337918
```


Total KWh

```
> TotalKWhhigh := KWhhigh + KWhQuooker;
                                             TotalKWhhigh := 3763.393333
> TotalKWhlow := KWhlow + KWhQuooker;
                                             TotalKWhlow := 2294.907083
```

Total Cost

```
> TotalCosthigh := Costhigh + CostQuooker;
                                             TotalCosthigh := 1430.089467
> TotalCostlow := Costlow + CostQuooker;
                                             TotalCostlow := 872.0646917
```

Total CO2eq

```
> TotalCO2eqlowDWquooker := Carbonfootprintlow + CarbonfootprintQuooker;
  TotalCO2eqhighDWquooker = Carbonfootprinthigh + CarbonfootprintQuooker;
                                             TotalCO2eqlowDWquooker := 1177.287334
                                             TotalCO2eqhighDWquooker = 1930.620780
```

Energy/CO2eq/Cost reduction according to paper dishwasher attached to fin tube heat exchanger

```
> restart;
> KWhlow := 0.113;
  KWhhigh := 0.271;
  Energycost := 0.38;
  Days := 365;
  Useperday := 1;
  Lifespan := 10;
  CO2kgeqperKWh := 0.513;
  TotalKWhlow := 1849.91;
  TotalKWhhigh := 3318.40;
                                             KWhlow := 0.113
                                             KWhhigh := 0.271
                                             Energycost := 0.38
                                             Days := 365
                                             Useperday := 1
                                             Lifespan := 10
                                             CO2kgeqperKWh := 0.513
                                             TotalKWhlow := 1849.91
                                             TotalKWhhigh := 3318.40
> KWhlowlifespan := KWhlow·Days·Useperday·Lifespan;
  KWhhighlifespan := KWhhigh·Days·Useperday·Lifespan;
                                             KWhlowlifespan := 412.450
                                             KWhhighlifespan := 989.150
> Carbonfootprintlow := KWhlowlifespan·CO2kgeqperKWh;
  Carbonfootprinthigh := KWhhighlifespan·CO2kgeqperKWh;
                                             Carbonfootprintlow := 211.586850
                                             Carbonfootprinthigh := 507.433950
> Costlowreduction := Energycost·KWhlowlifespan;
                                             Costlowreduction := 156.73100
> Costhighreduction := Energycost·KWhhighlifespan;
                                             Costhighreduction := 375.87700
> Percentagereductionlow := KWhlowlifespan/TotalKWhlow·100;
  Percentagereductionhigh := KWhhighlifespan/TotalKWhhigh·100;
                                             Percentagereductionlow := 22.29567925
                                             Percentagereductionhigh := 29.80804002
```

A2: Interviews users

INTERVIEW 1

Age: 28
Living arrangement: Living with her partner
House type: Owns a house (bought a newly built apartment a year ago), apartment

Do you have a Quooker system? Why/are you (not) interested in it?
My parents had a Quooker and I liked it. When they were purchasing a new kitchen, they chose to buy a Quooker. They opted only for the tap and kettle because the price increase was significant to buy the CUBE too. The kitchen was already pricey, so they had to make choices. They both like the convenience of having chilled and sparkling water. For this, a soda stream would have been a good option too. If it had added 300 euros to the price, she would have wanted a CUBE too.

Do you make sustainable choices? How is that evident? Why not?
I am a flexitarian, don't t own a car, partly because they don't have a traffic permit, and I don't buy fast fashion clothing. I don't pay much attention to sustainability with groceries. I sell my clothes second-hand but doesn't buy second-hand myself. I do like new things. Me and my partner are conscious though, so we have an ANWB subscription where we can see when it's best to use energy. It's advantageous for us in terms of money, but it's also more sustainable. I am aware that we all need to be aware of sustainability and thus making sustainable choices makes me feel good. I do not consume more than I need.

Do you have energy-saving products in your house (such as solar panels or a shower WTW system)? Why?
We have a good energy label. We have a well-insulated house. Low-temperature heating, good HR++ glass for the windows. We would like to have a heat pump and solar panels. The contractor didn't want to install a heat pump. First, they would like to save money for solar panels, but after saving more money, we also want a heat pump.

Would you be open to purchasing a new energy-saving product? What do you focus on (MONEY OR SUSTAINABILITY)? List them in order of importance from most to least important.
1. Return on investment (money)
2. Purchase price
3. Whether it fits in the space
4. Noise/disruption
5. Appearance
6. Size

How much should an energy-saving product cost? Why?
I would mainly look at the return on investment. Suppose the limit is that it pays back in 7 years and then spend a maximum of 8000 euros at once. It also matters how much the product you buy raises the energy label of your house.

Would you still find an energy-saving product interesting if it reduces more net CO2 emissions than it took to make it if it is not net cost-efficient? Why? What's the nuance?
It depends on how inefficient it is and how much impact it makes. If it makes a lot of impact and you don't incur much loss, I would seriously consider it. Otherwise not.

What should be the maximum time for a product to pay itself back? Explain.
I do not see myself living in the same house for the rest of her life. If I live in a house where I will stay longer, I would like to purchase such a product. Unless it already increases the value of the house, then it doesn't matter.

If you could think of an energy-reducing product for warm water in the kitchen, what would you take into consideration?
How it would work. If it works in our kitchen, also in size. How it looks in our kitchen. How much it saves, what it saves (in price or energy). What the payback period is. The price of the device itself ,whether you can afford it at that time.
The price and the payback time. And how quickly it pays itself back. I would be more willing to invest in this energy-reducing concept than the CUBE. I would mainly consider to buy such a product when we are buying a new kitchen or making a major change in energy reduction products in the house.

INTERVIEW 2

Age: 59
Living arrangement: Living alone
House type: Owns a house

Do you have a Quooker system? Why/are you (not) interested in it?
No, I do not have a Quooker system. I would be interested in it. However, I am more interested in the chilled and sparkling water. If I would buy a Quooker system I would buy both the Quooker kettle and the CUBE. However, right now I find it a hassle, so I would consider buying this only when I gets a new kitchen.

Do you make sustainable choices? How is that evident? Why not?
Yes, I believe I do sometimes. I installed solar panels 6 years ago. I rent them because of the high initial price. Still, I wanted to have the solar panels. I did it out of idealism. Additionally, I do not heat the house too much and I try to be economical, but a warm house is comfortable. I do not fly much, and I try not to buy too much new clothes.

Do you have energy-saving products in your house (such as solar panels or a shower heat recovery system)? Why?
My house is well insulated. However, I have no electric car, because it is too expensive. Then you have to charge your car when the sun is shining. There is uncertainty about when to use them, the solar panels. How does it work exactly? You use it at times when you don't generate it. The purchase price too high. So, it really depends on the costs, but the idealism remains.

Would you be open to purchasing a new energy-saving product? What do you focus on (economic value or sustainability)? List them in order of importance from most to least important.

I would first look whether a product looks appealing to me. However, I only buy a new device when the other one is broken and if it saves a lot. I do not just buy new things. This is also a result of me living alone in the house. Therefore, purchase cost, installation and orientation are important for me. I would like a Quooker CUBE because I finds it nonsense to buy bottles with sparkling water. I had a Soda Stream device, but it broke. That's a very ugly thing, so that helps. Comparing different options for the same solution would be helpful to narrow down.
1. Appearance
2. Sustainability
3. Costs
4. Installation

How much should an energy-saving product cost? Why?
If you buy a washing machine and it's 200 euros more expensive and sustainable, it's okay. Not more than 25 to 30 percent more expensive than the price of a regular washing machine.

Would you still find an energy-saving product interesting if it reduces more net CO2 emissions than it took to make it if it is not net cost-efficient? Why? What's the nuance?
Then it becomes too difficult. Then I would wait until such a product is further developed and works better. The first people to choose a new product are initially the richer people.

What should be the maximum time for a product to pay itself back? Explain
It's more interesting for someone who uses this more often. On the total budget of the kitchen, 500 euros extra is fine if it pays back in 10 years.

What should be the maximum purchase costs? Explain
Not more than 800 euros.

INTERVIEW 3

Age: 51
Living arrangement: Living with a partner
House type: Owns a house

Do you have a Quooker system? Why/would you be interested in it?
We had a Quooker in the old kitchen, next to the regular tap. After that, we didn't want to live without it anymore. When we moved, there was already a Quooker tap in the kitchen. Therefore, we decided to connect the two Quooker taps to the kettle. We didn't feel the need for cold water and sparkling water. The boiling water system was so convenient for us because we thought boiling water took too long with a small water kettle, and we drink a lot of tea at home.

Do you make sustainable choices? How is that evident? Why not?
Not extremely. We have solar panels and a heat pump. Additionally, we the extension we made in the new house is made with recycled materials. I buy second-hand clothing and we do recycle a lot. When it comes to materials, we see if we already own something that could help us out. For example, we don't necessarily want to purchase more sustainable clothing or buy more in the supermarket, we rather use old materials we already own. Also, we pay more attention to products that last longer. Yes, and lastly, we put the heater lower and use more blankets to keep us warm in the colder days.

Do you have energy-saving products in your house (such as solar panels or a shower heat recovery system)? Why?
Considering the shower heat recovery, some pipes need to be installed. Nevertheless, we do consider a shower heat recovery system. That also has to do with investment or whether it is worthwhile. For the solar panels: we have twelve or 15 of them on the roof. We did this 8 years ago because it fitted nicely on the roof and they would be positioned in the sun. With the extension, when we were going to set up a sunroof anyway, why not also solar panels? We also really pay attention to costs, it has also been a cost investment. And we also pay attention to what moment of the day we turn on the washing machine. We do this to consume electricity when it is generated. For the old part of this house, we don't have a heat pump. This is because we have an old house. In many rooms, it was not useful. When we had the extension, we wanted a heat pump. To see if we could get off the gas. Our motivation was both cost and sustainability.

Would you be open to purchasing a new energy-saving product? What do you focus on ()? List them in order of importance from most to least important.
I would be interested in the power consumption, a device must be functional, and user-friendly. You have to benefit from it. I don't need a soda stream because I think we would not use it much. We would pay attention to whether we can repair products ourselves, so repairability is important to us. Sustainable in that way. Modular building. Small rings that are lost. Our motto is: 'It's only broken if it's not repairable anymore'. If a HEX can go under a plinth, or would not use much space, I would love to have it.

1. Cost
2. Functionality
3. Space
4. User-friendliness & Repair
5. Sustainability

Would you still find an energy-saving product interesting if it reduces more net CO2 emissions than it has cost to make it if it is not net cost-efficient? Why? What is the nuance?
It must be sustainable below the line. Costs are less important than sustainability.

What should be the maximum time for a product to pay itself back? Explain
That is a difficult one to answer, it depends. I think about 3 years. With a heat pump or a solar panel, it's longer for us.

INTERVIEW 4

Age: 57
Living arrangement: Living with a partner
House type: Owns a house

Do you have a Quooker system? Why/are you (not) interested in it?
I have a Quooker system. I wanted boiling water quickly. Also for the warm water, it was important for me that I would get that quickly. Think of cleaning etc.. Additionally, I love to drink tea, so that was also an important factor.

Do you make sustainable choices? How is that evident? Why not?
Yes, I do believe I make sustainable choices. That means that I choose products that in my eyes are durable and have a long lifespan. I have ceramic stones in the garden that will not fade or break easily, the same for my kitchen counter. These choices are often expensive, but I rather have a product that is durable and that I would like to own for a long time. This does mean that we do have to have the money to be able to make these kind of decisions. I also pay attention to the toxicity of products. In my garden I would like to only use products that are nature friendly. I do not like clothes that are fast fashion. I rather buy an expensive piece of clothing that is made out of natural materials and that lasts long, than an inexpensive piece that quickly breaks down.

Do you have energy-saving products in your house (such as solar panels or a shower heat recovery system)? Why?
We have solar panels and our house is labelled as AAA. It is nice that we do not pay a lot of money then and we are not using a lot of energy to heat up this house. We have quite a big house, so it is quite unique to use so little energy to heat up the house. When this house was built, we chose to have the solar panels to be more energy efficient. However, I recently found out that it is not so sustainable to make solar panels and to throw them away when they are not working accordingly anymore. Therefore I doubt whether I made the right decision, but they are already on my roof so I will now use them of course.

Would you be open to purchasing a new energy-saving product? What do you focus on? List them in order of importance from most to least important.
Whether the product is durable, the quality of the product. Whether the product is aesthetically pleasing to me and whether it is net sustainable. Cost are in the end important too, but as I said before, I believe it is okay to pay more for a good product. But I would have to feel convinced on that part.
1. Aesthetically pleasing
2. Costs
3. Quality & durability
4. Net sustainability

I have to say with the costs, if I really believe that a product it sustainable and durable and looks good, then I am willing to pay more for the product. However, the cost can be an immediate deal breaker in case I do not feel like I want the product that much. This desire for a product for me is created by the aesthetics of a product, net sustainability and the quality and durability of a product.

How much should an energy-saving product in the kitchen cost? Why?
I really don't know. I can give an example of my range hood. I really did not want a range hood on my kitchen island that was attached to the ceiling. Therefore, I was looking into solutions that would fit in the countertop. I saw these products, found them aesthetically pleasing and functional with its extra benefits. I was immediately convinced, even though this product was almost double the price of a regular range hood. I have to say that once we chose to get the new kitchen, we were already paying a lot of money, so I wanted the kitchen to be exactly how I wanted it. Therefore paying more was at that moment not that much of a problem for an addition in my kitchen that I desired.

What should be the maximum time for a product to pay itself back? Explain
I really cannot say. In case we are talking about the kitchen, I believe that if you buy such a product, I expect it to last as long as I live there. But still, it is difficult to say because it also depends on the initial cost. Another important factor is that something is value retaining. I look at the whole package, everything together.

A3: USER TEST

HI,

Wat leuk dat je mee wilt doen met dit onderzoek! Je helpt mij hiermee om inzicht te krijgen in warm/heet watergebruik. Het enige wat je nodig hebt is een Quooker kraan, een pen, de tabellen en de tijd!

Voordat je begint

Beschrijf de samenstelling van je huishouden:

……………………………………………………………………………………

……………………………………………………………………………………

……………………………………………………………………………………

Ben je vaak in de keuken te vinden? Hoevaak en waarom?

……………………………………………………………………………………

……………………………………………………………………………………

……………………………………………………………………………………

In het kort:

In dit onderzoek is alleen het tappen en weggieten van warm **of heet water** van belang. Om die reden hoef je **koud of lauw (dat kouder aanvoelt dan je hand) watergebruik dus niet in te vullen!** Ik ben benieuwd naar de temperatuur van het water en het tijdsinterval tussen heet/warm water tappen en weggieten. Geen zorgen, de temperatuur van het water mag je schatten (zie tabel op de volgende pagina).

Het is de bedoeling dat je van **twee** (gebruikelijke) **doordeweekse** en **twee** (gebruikelijke) **weekend dagen** bij houdt wanneer je warm of heet water tapt, de vaatwasser gebruikt, of warm of heet water weggiet en in welk scenario. Let op: als je bijvoorbeeld extra mensen op bezoek hebt, kun je dit bovenaan de bladen invullen. In het meegegeven voorbeeld zie je hoe je de tabel kunt invullen.

Je kunt de ingevulde tabellen in de week van **8 tot 12** januari inleveren.

Succes! ☺

NUMMERS OPTIES VOOR IN DE LEGE TABELLEN

Tijd	Handeling	Hoeveelheid	Gelegenheid	Opmerking
………	1. Vaatwasser aanzetten 2. Kokend water tappen 3. Heet water tappen (niet met hand aan te raken) 4. Warm water tappen (wel met hand aan te raken) 5. (Nagenoeg) kokend water weggieten 6. Heet water weggieten (niet met hand aan te raken) 7. Warm water weggieten (wel met hand aan te raken)	1. Vaatwasser aan (……………graden), tijdsduur 2. Kopje/glaasje (0,3 L) 3. Mok/groot glas (0,5L) 4. Kleine pan (1L) 5. Middelgrote pan/kleine emmer (2,5L) 6. Grote pan/grote emmer (5 L) 7. Kraan open laten lopen: +/-……………………………sec (Hoe ver de kraan open?: ¼, ½, ¾, volledig) 8. Kokend/heet/warm/koud 9. Anders: ……………………………………(… L)	1. Vaatwasser aan 2. Koken 3. Afwassen (hand) 4. Drinken 5. Schoonmaken	……………… ……………… ……………… ………………

VOORBEELD: INGEVULDE TABEL

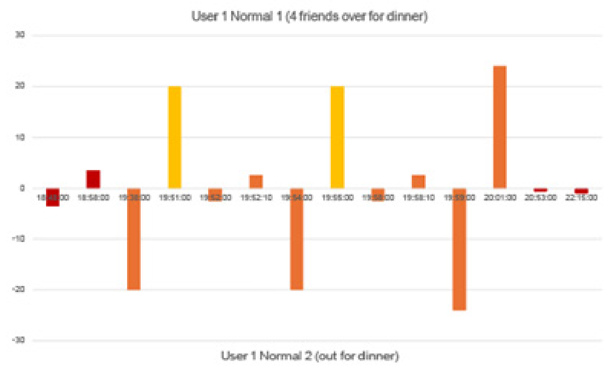
Doordeweekse dag 1: Woensdag 14 December **Bijzonderheden: +2 mensen op bezoek**

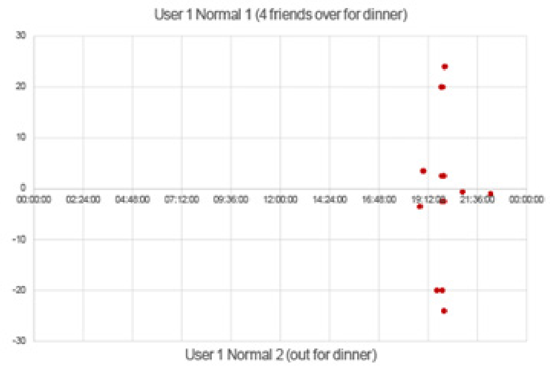
Tijd	Handeling	Hoeveelheid	Gelegenheid	Opmerking
(vb) 15:00	*(vb) 4 & 7*	*(vb) 7, 5 sec, ½ open*	*(vb) 3*	*(vb) Glas omspoelen*
(vb) 17:35	*(vb) 2*	*(vb) 5*	*(vb) 2*	*(vb) Groente koken*
(vb) 17:36	*(vb) 2*	*(vb) 6*	*(vb) 2*	*(vb) Pasta koken*
(vb) 17:50	*(vb) 4*	*(vb) 5*	*(vb) 2*	*(vb) Groente afgieten*
(vb) 17:51	*(vb) 4*	*(vb) 6*	*(vb) 2*	*(vb) Pasta afgieten*
(vb) 18:15	*(vb) 1*	*(vb)* 1, 60 graden, ongeveer 2 uur	*(vb)* 1	*(vb) Vaatwasser aan*
(vb) 18:35	*(vb) 3*	*(vb)* 5	*(vb)* 5	*(vb) Keuken schoonmaken*
(vb) 18:45	*(vb) 7*	*(vb)* 5	*(vb)* 5	*(vb)* Emmer afgieten
(vb) 20:00	*(vb) 2*	*(vb)* 4	*(vb)* 4	*(vb)* Pot thee zetten
(vb) 20:45	*(vb) 7*	*(vb) 2*	*(vb)* 4	*(vb) Overige thee weggieten*

A4: USER TEST OUTCOMES

Week day 1: Four friends over for dinner
This user uses plenty of hot water while doing the dishes. It became clear that the user leaves the tap open during doing the dishes. In the evening the tap was used to fill a hot water bottle and for tea.

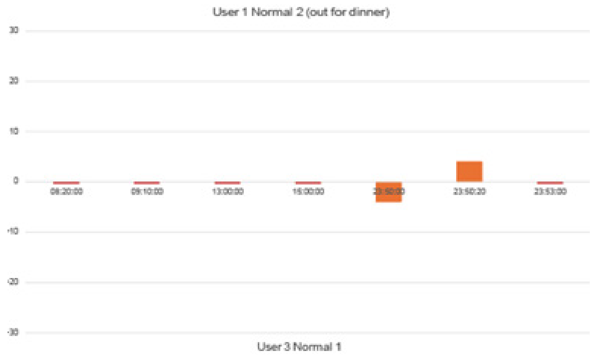
Time	Amount	Temperature	Occasion	Note
18:48	-3.5	Boil	Cooking	
18:58	3.5	Boil	Cooking	
19:38	-20	Hot	Dishes	Sink full
19:51	20	Warm	Dishes	Emptying sink
19:52	-2.5	Hot	Dishes	Wash pans
19:52	2.5	Hot	Dishes	Wash pans
19:54	-20	Hot	Dishes	Sink full
19:55	20	Warm	Dishes	Emptying sink
19:58	-2.5	Hot	Dishes	Wash pans
19:58	2.5	Hot	Dishes	Wash pans
19:59	-24	Hot	Dishes	Wash pans
20:01	24	Hot	Dishes	Wash pans
20:53	-0.6	Boil	Drink	Tea
22:15	1	Boil	Other	Hot water bottle

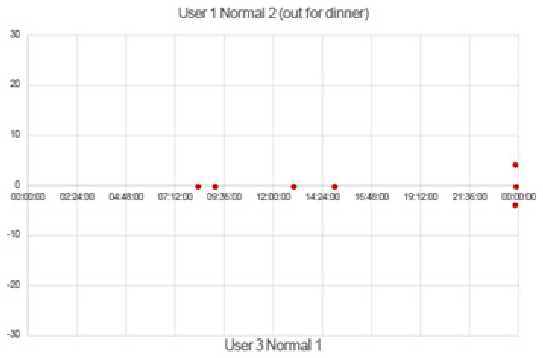




Week day 2 : Out for dinner
A little amount of water was tapped and drained as a result of going out for dinner. There was more tapping behavior than draining.

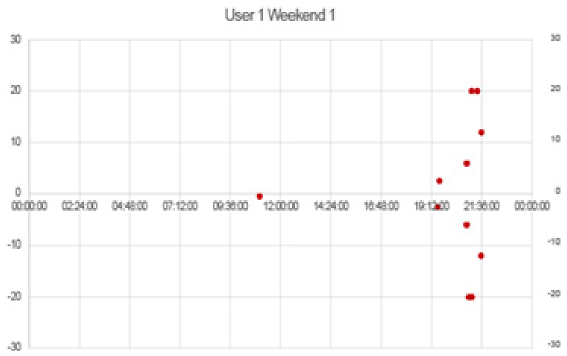
Time	Amount	Temperature	Occasion	Note
08:20	-0.3	Boil	Cooking	Breakfast
09:10	-0.3	Boil	Cooking	Breakfast
13:00	-0.3	Boil	Drink	Tea
15:00	-0.3	Boil	Drink	Tea
23:50	-4	Hot	Dishes	Wash mugs
23:50	4	Hot	Dishes	Wash mugs
23:53	-0.3	Boil	Drink	Tea





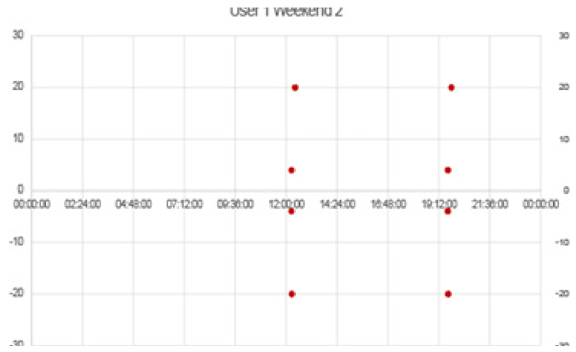
Weekend day 1 :
This time, this user first filled the sink to do the dishes, after which the user empties the sink. The user has different behavior in terms of doing the dishes per day.

Time	Amount	Temperature	Occasion	Note
11:00	-0.5	Boil	Drink	Tea
19:30	-2.5	Boil	Cooking	Cooking
19:35	2.5	Boil	Cooking	Draining
20:53	-6	Hot	Dishes	Prewash
20:53	6	Hot	Dishes	Prewash
20:59	-20	Hot	Dishes	Dishes
21:07	20	Warm	Dishes	Dishes
21:08	-20	Hot	Dishes	Dishes
21:23	20	Warm	Dishes	Dishes
21:34	-12	Hot	Dishes	Wash pans
21:35	12	Hot	Dishes	Wash pans



Weekend day 2 :
Again, the sink was first filled, then the dishes were done, after which the sink was emptied. The user rinses the dishes with hot water.

Time	Amount	Temperature	Occasion	Note
12:15	-4	Hot	Dishes	Wash pans
12:15	4	Hot	Dishes	Wash pans
12:16	-20	Hot	Dishes	Sink full
12:25	20	Warm	Dishes	Emptying sink
19:37	-4	Hot	Dishes	Wash pans
19:37	4	Hot	Dishes	Wash pans
19:38	-20	Hot	Dishes	Sink full
19:47	20	Warm	Dishes	Emptying sink

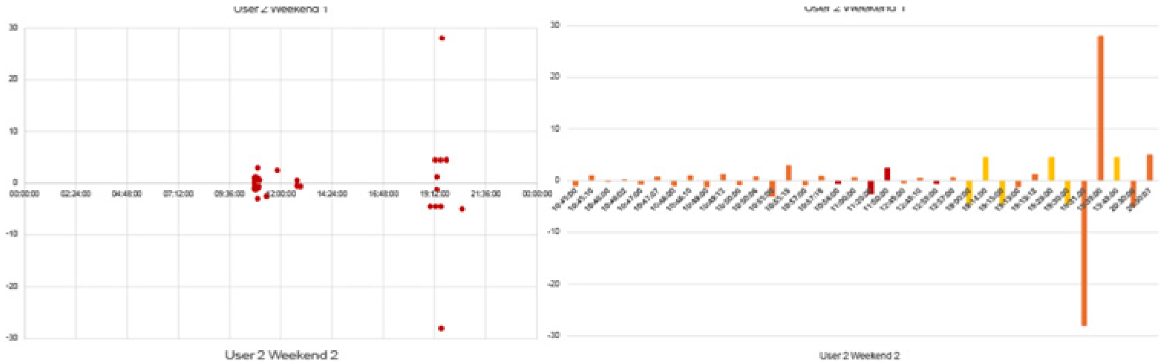


PARTICIPANT 2

Weekend day 1 :
This user uses small to medium amounts of water during the whole day, starting early in the morning. Next to the dishwasher, plenty of dishes are done, by tapping small amounts of water. The tap is turning on-and off

Time	Amount	Temperature	Occasion	Note
10:45	-1	Hot	Dishes	Dishes
10:45	1	Hot	Dishes	Dishes
10:46	-0.2	Hot	Dishes	Dishes
10:46	0.2	Hot	Dishes	Dishes
10:47	-0.7	Hot	Dishes	Dishes
10:47	0.7	Hot	Dishes	Dishes
10:48	-1	hot	Dishes	Dishes
10:48	1	Hot	Dishes	Dishes
10:49	-1.2	Hot	Dishes	Dishes
10:49	1.2	Hot	Dishes	Dishes
10:50	-0.8	Hot	Dishes	Dishes
10:50	0.8	Hot	Dishes	Dishes
10:55	-3	Hot	Dishes	Dishes
10:55	3	Hot	Dishes	Dishes
10:57	-0.9	Hot	Dishes	Dishes
10:57	0.9	Hot	Dishes	Dishes
10:58	-0.6	Boil	Drink	Preheating mug
11:00	0.6	Hot	Drink	Preheating mug
11:20	-2.5	Boil	Cooking	Cooking
11:50	2.5	Boil	Cooking	Cooking
12:45	-0.5	Hot	Dishes	Dishes
12:45	0.5	Hot	Dishes	Dishes
12:55	-0.6	Boil	Drink	Preheating mug
11:00	0.6	Hot	Drink	Preheating mug

19:00	-4.5	Warm	Dishwasher	Cycle 1 (45 degrees, 45min)
19:14	4.5	Warm	Dishwasher	Cycle 1
19:15	-4.5	Warm	Dishwasher	Cycle 2
19:19	-1.2	Hot	Dishes	Dishes
19:19	1.2	Hot	Dishes	Dishes
19:29	4.5	Warm	Dishwasher	Cycle 2
19:30	-4.5	Warm	Dishwasher	Cycle 3
19:31	-28	Hot	Dishes	Dishes
19:33	28	Hot	Dishes	Dishes
19:45	4.5	Warm	Dishwasher	Cycle 3
20:30	-5	Hot	Dishes	Dishes



Weekend day 2 :
This user leaves the tap open while doing the dishes, sometimes using plenty of water in one go, other times by quickly opening and closing the tap. The water temperatures differ from hot to warm when doing the dishes.

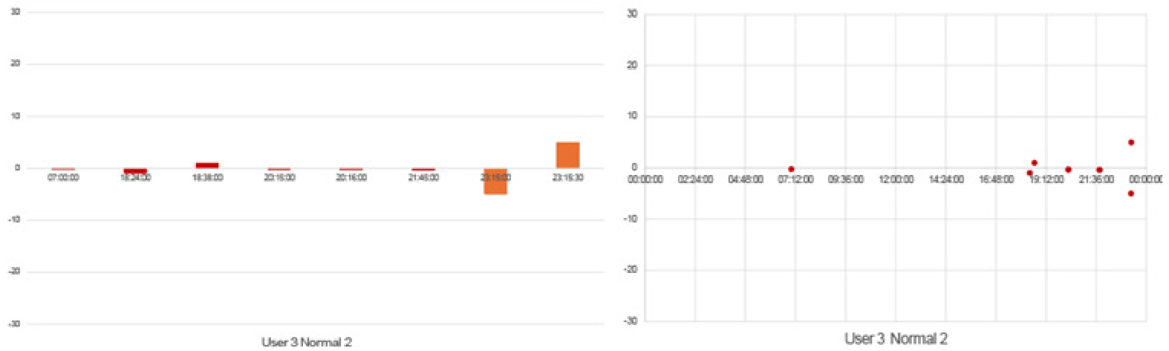
Time	Amount	Temperature	Occasion	Note
11:45	-0.6	Boil	Drink	Preheating mug
11:46	0.6	Hot	Drink	Preheating mug
11:57	-0.8	Warm	Dishes	Dishes
11:57	0.8	Warm	Dishes	Dishes
14:00	-0.3	Boil	Drink	Preheating mug
14:01	0.3	Hot	Drink	Preheating mug
14:30	-4	Warm	Cleaning	Filling bucket
14:45	4	Warm	Cleaning	Emptying bucket
16:20	-0.4	Warm	Cooking	Making dough
16:21	0.2	Warm	Cooking	Pooring away leftover water
16:40	-4.8	Warm	Dishes	Wash pans
16:40	4.8	Warm	Dishes	Dishes
18:32	-1	Warm	Dishes	Dishes
18:32	1	Warm	Dishes	Dishes
19:50	-19.5	Hot	Dishes	Dishes
19:50	19.5	Hot	Dishes	Dishes
19:52	-4.4	Boil	Dishes	Dishes
19:52	4.4	Boil	Dishes	Dishes
19:55	-3.4	Warm	Cleaning	Cleaning
19:55	3.4	Warm	Cleaning	Cleaning
23:05	-2.5	Warm	Dishes	Dishes
23:05	2.5	Warm	Dishes	Dishes

23:10	-4.5	Warm	Dishwasher	Cycle 1 (50 degrees, 4:45min)
23:11	4.5	Warm	Dishwasher	Cycle 1
01:02	-4.5	Warm	Dishwasher	Cycle 2
01:03	4.5	Warm	Dishwasher	Cycle 2
02:54	-4.5	Warm	Dishwasher	Cycle 3
02:55	4.5	Warm	Dishwasher	Cycle 3

PARTICIPANT 3

Week day 1 :
The user did not turn on the dishwasher. Little amount of water was drained.

Time	Amount	Temperature	Occasion	Note
07:00	-0.25	Boil	Drink	Tea
18:24	-1	Boil	Cooking	Filling pan
18:38	1	Boil	Cooking	Draining pan
20:15	-0.3	Boil	Drink	Tea
20:16	-0.3	Boil	Drink	Tea
21:45	-0.4	Boil	Drink	Tea
23:15	-5	Hot	Dishes	
23:15	5	Hot	Dishes	

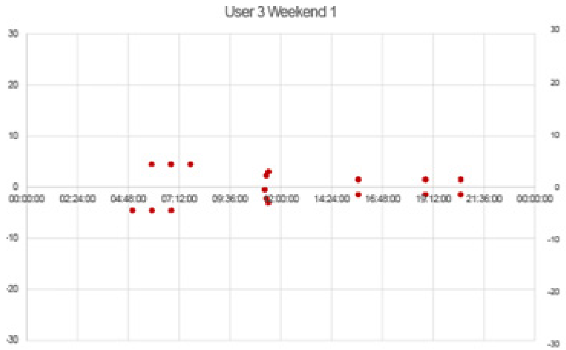


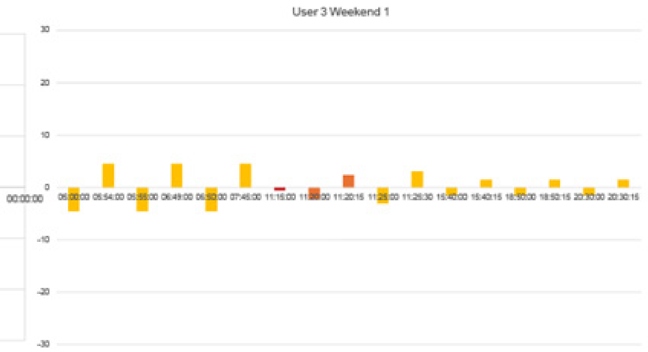
Week day 2: Did not cook
This user turns the dishwasher on at night. Taps boiling water early in the morning and in the evening for tea, in small amounts.

Time	Amount	Temperature	Occasion	Note
05:00	-4.5	Warm	Dishwasher	Cycle 1 (45-65 degrees, 2h45)
05:54	4.5	Warm	Dishwasher	Cycle 1
05:55	-4.5	Warm	Dishwasher	Cycle 2
06:49	4.5	Warm	Dishwasher	Cycle 2
06:50	-4.5	Warm	Dishwasher	Cycle 3
07:45	4.5	Warm	Dishwasher	Cycle 3
11:15	-0.5	Boil	Drink	Tea
11:20	-2.25	Hot	Dishes	
11:20	2.25	Hot	Dishes	
11:25	-3	Warm	Dishes	
11:25	3	Warm	Dishes	
15:40	-1.5	Warm	Wash hands	
15:40	1.5	Warm	Wash hands	
18:50	-1.5	Warm	Wash hands	
18:50	1.5	Warm	Wash hands	
20:30	-1.5	Warm	Wash hands	
20:30	1.5	Warm	Wash hands	

Weekend day 2:
The dishwasher was turned on at night. Additional dishes were done throughout the whol evening.

Time	Amount	Temperature	Occasion	Note
04:00	-4.5	Warm	Dishwasher	Cycle 1 (45-65 degrees, 2h45)
04:54	4.5	Warm	Dishwasher	Cycle 1
04:55	-4.5	Warm	Dishwasher	Cycle 2
05:49	4.5	Warm	Dishwasher	Cycle 2
05:50	-4.5	Warm	Dishwasher	Cycle 3
06:45	4.5	Warm	Dishwasher	Cycle 3
16:00	-0.5	Boil	Drink	Tea
17:50	-1.5	Hot	Dishes	
17:50	1.5	Hot	Dishes	
19:00	-4.5	Hot	Dishes	
19:00	4.5	Hot	Dishes	
23:10	-1	Hot	Dishes	
23:10	1	Hot	Dishes	
23:30	-3	Hot	Dishes	
23:30	3	Hot	Dishes	
23:35	-0.5	Warm	Wash hands	
23:35	0.5	Warm	Wash hands	

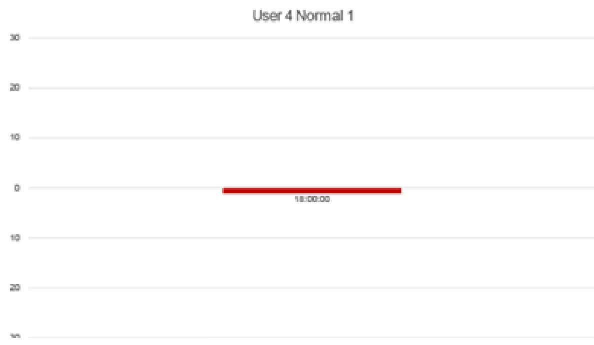


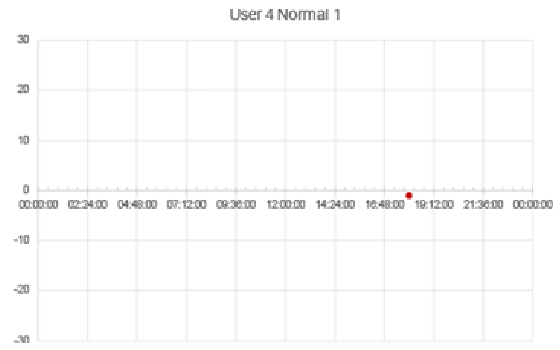


PARTICIPANT 4

Week day 1 :
This user only used one pan of boiling water for cooking, without draining the water.

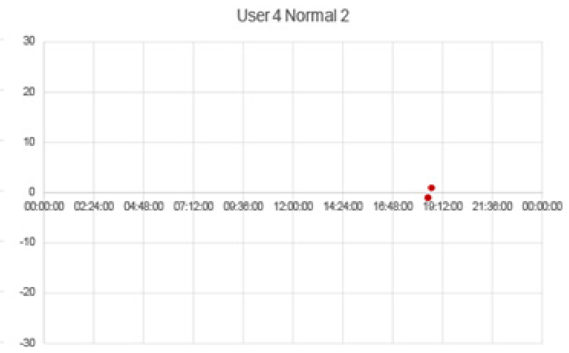
Time	Amount	Temperatu	Occasion	Note
18:00	-1	Boil	Cooking	





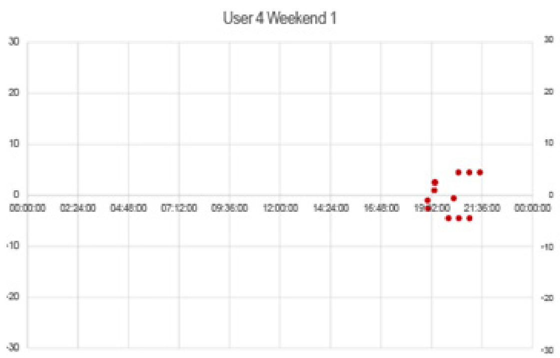
Week day 2:
The user only used one pan of boiling water for cooking and then drained the pan with boiling water 10 minutes later.

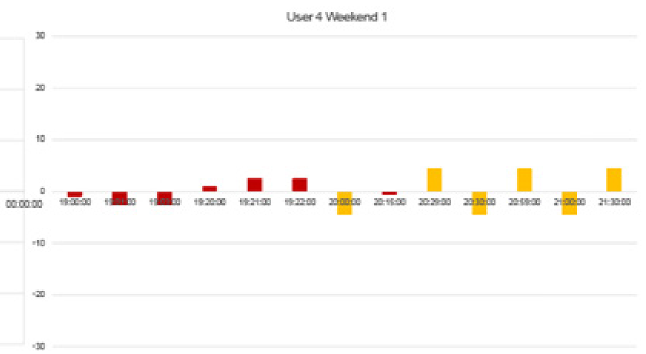
Time	Amount	Temperatu	Occasion	Note
18:30	-1	Boil	Cooking	
18:40	1	Boil	Cooking	



Weekend day 1:
Three pans of boiling water were tapped and drained during cooking. The pans were quickly after one another drained. The dishwasher was turned on 40 minutes after draining the pans of boiling water.

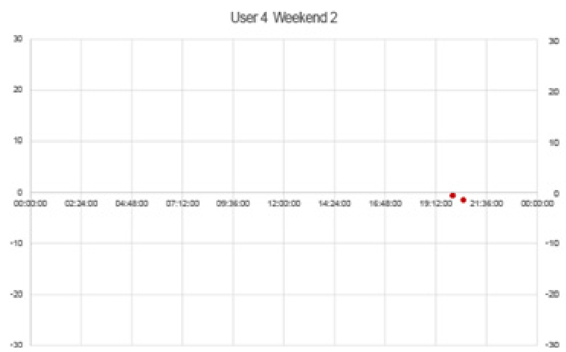
Time	Amount	Temperati	Occasion	Note
19:00	-1	Boil	Cooking	Egg
19:01	-2.5	Boil	Cooking	Mie
19:03	-2.5	Boil	Cooking	Broccoli
19:20	1	Boil	Cooking	Draining
19:21	2.5	Boil	Cooking	Draining
19:22	2.5	Boil	Cooking	Draining
20:00	-4.5	Warm	Dishwasher	Cycle 1 (70 degrees, 1h30)
20:15	-0.6	Boil	Drink	Tea
20:29	4.5	Warm	Dishwasher	Cycle 1
20:30	-4.5	Warm	Dishwasher	Cycle 2
20:59	4.5	Warm	Dishwasher	Cycle 2
21:00	-4.5	Warm	Dishwasher	Cycle 3
21:30	4.5	Warm	Dishwasher	Cycle 3

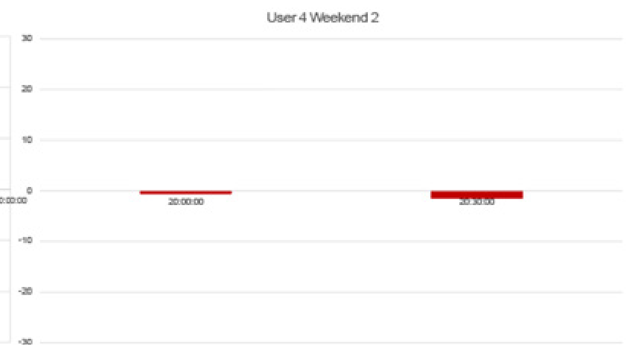




Weekend day 2 :
No water was drained during this day.

Time	Amount	Temperati	Occasion	Note
20:00	-0.6	Boil	Drink	Tea
20:30	-1.5	Boil	Cooking	Hot water bottle

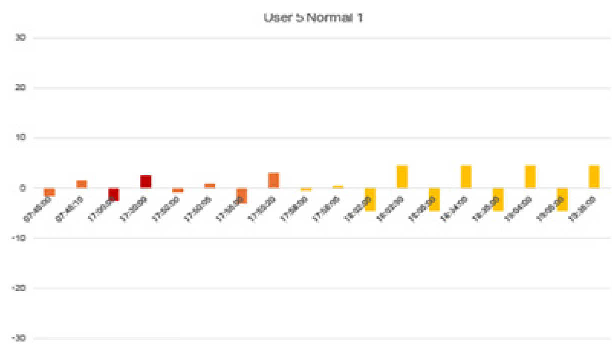


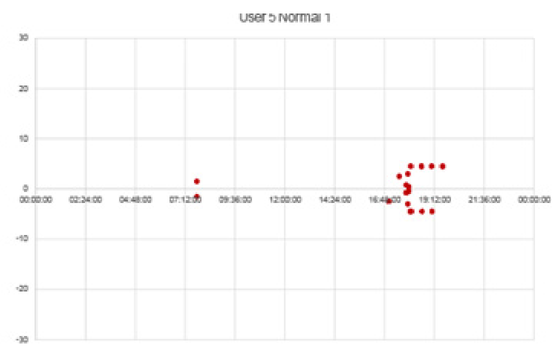


PARTICIPANT 5

Week day 1 :
Pans were quickly rinsed before going into the dishwasher. Dishwasher was turned on around 35 minutes after draining boiling water after cooking.

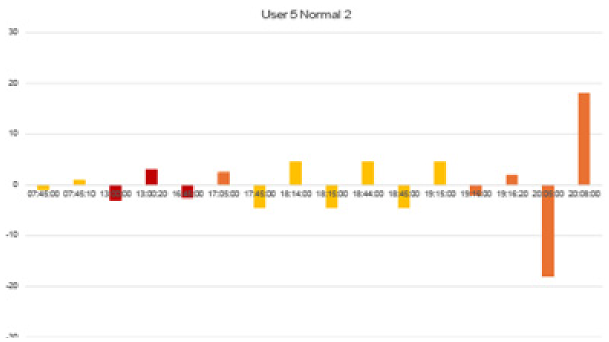
Time	Amount	Temperature	Occasion	Note
00:00:00				
07:45:00	-1.5	Hot	Dishes	Childrens breakfast
07:45:10	1.5	Hot	Dishes	
17:00:00	-2.5	Boil	Cooking	Pasta
17:30:00	2.5	Boil	Cooking	Draining
17:50:00	-0.75	Hot	Dishes	Dishes
17:50:05	0.75	Hot	Dishes	Dishes
17:55:00	-3	Hot	Dishes	Quick rinse pan before DW
17:55:20	3	Hot	Dishes	Quick rinse pan before DW
17:58:00	-0.45	Warm	Cleaning	Cleaning cloth
17:58:00	0.4	Warm	Cleaning	Cleaning cloth
18:02:00	-4.5	Warm	Washing hands	Washing hands
18:03:30	4.5	Warm	Washing hands	Washing hands
18:05:00	-4.5	Warm	Dishwasher	Cycle 1 (50 degrees, 1:30h)
18:34:00	4.5	Warm	Dishwasher	Cycle 1
18:35:00	-4.5	Warm	Dishwasher	Cycle 2
19:04:00	4.5	Warm	Dishwasher	Cycle 2
19:05:00	-4.5	Warm	Dishwasher	Cycle 3
19:35:00	4.5	Warm	Dishwasher	Cycle 3

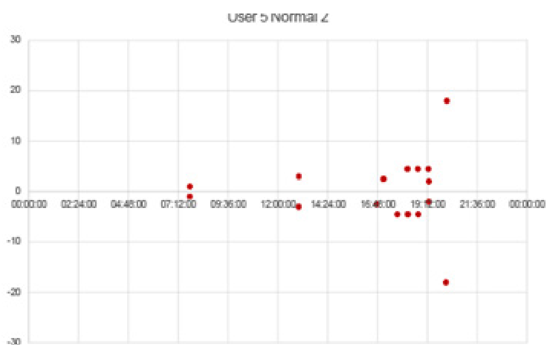




Week day 2:
The dishwasher was turned on 40 minutes after draining boiling water after cooking. In the morning and in the evening additional hand wash dishes were done.

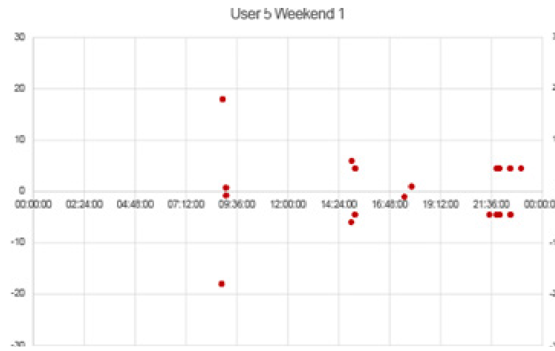
Time	Amount	Temperature	Occasion	Note
00:00:00				
07:45:00	-1	Warm	Dishes	Childrens breakfast
07:45:10	1	Warm	Dishes	
13:00:00	-3	Boil	Dishes	Pan
13:00:20	3	Boil	Dishes	Pan
16:45:00	-2.5	Boil	Cooking	Cooking
17:05:00	2.5	Hot	Cooking	Cooking
17:45:00	-4.5	Warm	Dishwasher	Cycle 1 (50 degrees, 1:30h)
18:14:00	4.5	Warm	Dishwasher	Cycle 1
18:15:00	-4.5	Warm	Dishwasher	Cycle 2
18:44:00	4.5	Warm	Dishwasher	Cycle 2
18:45:00	-4.5	Warm	Dishwasher	Cycle 3
19:15:00	4.5	Warm	Dishwasher	Cycle 3
19:16:00	-2	Hot	Dishes	Cleaning milk foamer
19:16:20	2	Hot	Dishes	Cleaning milk foamer
20:05:00	-18	Hot	Dishes	Dishwasher was full
20:08:00	18	Hot	Dishes	Dishwasher was full





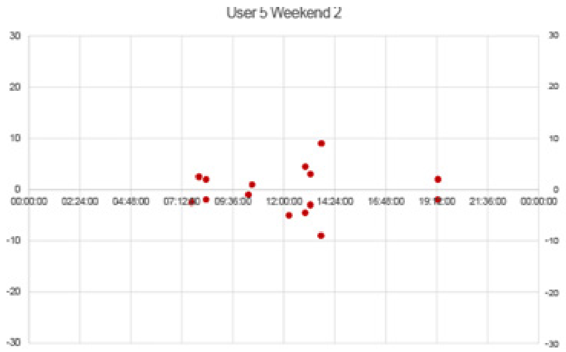
Weekend day 1:
Plenty of warm water was used to clean the shoes of the child.

Time	Amount	Temperature	Occasion	Note
00:00:00				
08:53:00	-18	Warm	Cleaning	Cleaning shoes child
08:56:00	18	Warm	Cleaning	Cleaning shoes child
09:05:00	-0.75	Hot	Dishes	Breakfast bowl
09:05:05	0.75	Hot	Dishes	Breakfast bowl
15:00:00	-6	Warm	Cleaning	Washing hands
15:01:00	6	Warm	Cleaning	Washing hands
15:10:00	-4.5	Warm	Cleaning	Washing hands
15:10:30	4.5	Warm	Cleaning	Washing hands
17:30:00	-1	Hot	Cooking	Warming up food
17:50:00	1	Hot	Cooking	Warming up food
21:30:00	-4.5	Warm	Dishwasher	Cycle 1
21:50:00	-4.5	Warm	Cleaning	Washing hands
21:50:30	4.5	Warm	Cleaning	Washing hands
21:59:00	4.5	Warm	Dishwasher	Cycle 1
22:00:00	-4.5	Warm	Dishwasher	Cycle 2
22:29:00	4.5	Warm	Dishwasher	Cycle 2
22:30:00	-4.5	Warm	Dishwasher	Cycle 3
23:00:00	4.5	Warm	Dishwasher	Cycle 3

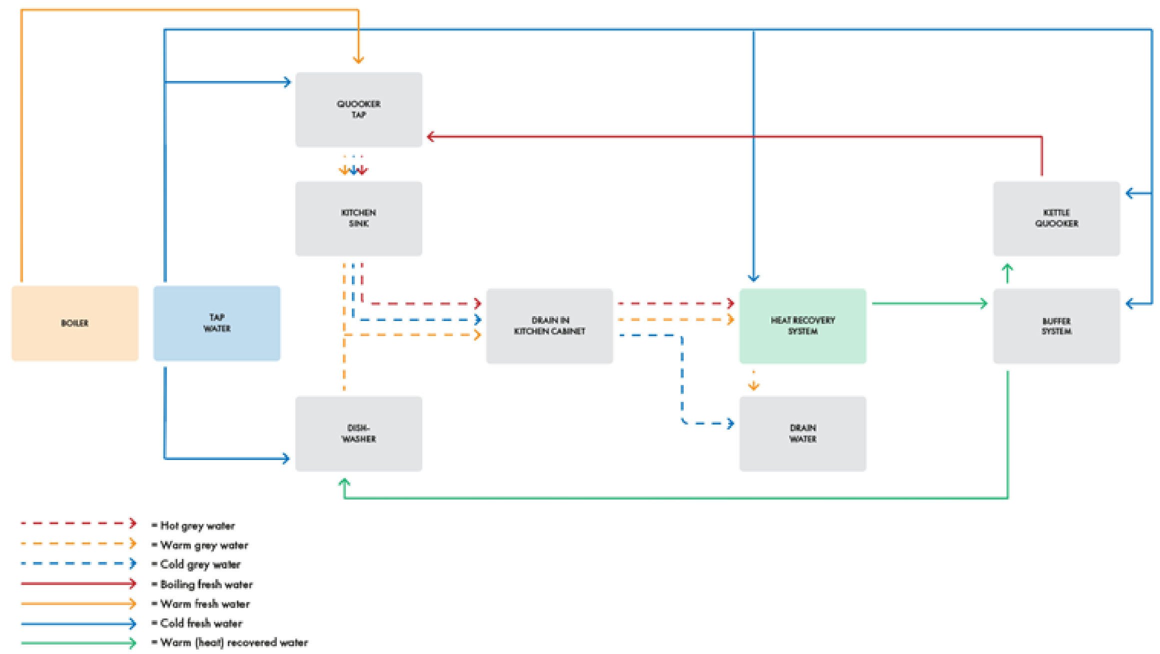


Weekend day 2:
Multiple small amounts of water were tapped and drained for different actions.

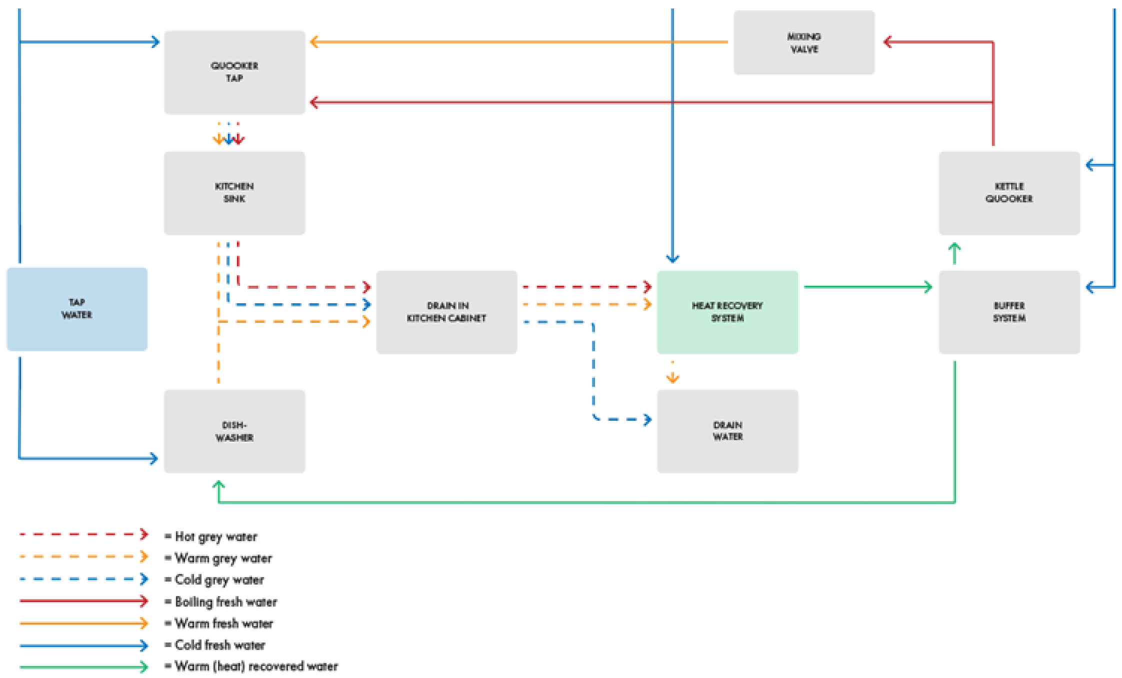
Time	Amount	Temperature	Occasion	Note
00:00:00				
07:40:00	-2.5	Warm	Dishes	Cleaning baby bucket
08:00:00	2.5	Warm	Dishes	Cleaning baby bucket
08:20:00	-2	Hot	Dishes	Cleaning milk foamer
08:20:20	2	Hot	Dishes	Cleaning milk foamer
10:20:00	-1	Boil	Cooking	Boiling eggs
10:30:00	1	Boil	Cooking	Boiling eggs
12:15:00	-5	Hot	Cleaning	Wash car
13:00:00	-4.5	Warm	Cleaning	Washing hands
13:00:30	4.5	Warm	Cleaning	Washing hands
13:15:00	-3	Hot	Dishes	Cleaning milk foamer
13:15:20	3	Hot	Dishes	Cleaning milk foamer
13:45:00	-9	Warm	Cleaning	Cleaning paintbrush
13:46:00	9	Warm	Cleaning	Cleaning paintbrush
19:15:00	-2	Warm	Dishes	Cleaning milk foamer
19:15:20	2	Warm	Dishes	Cleaning milk foamer



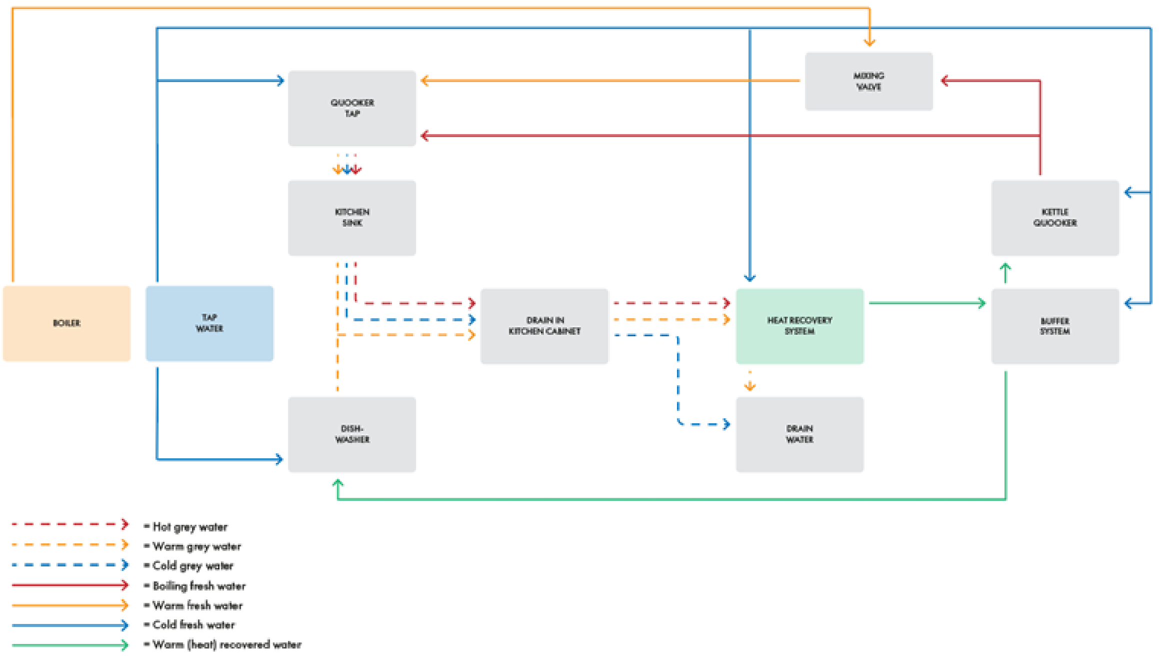
A5: QUOOKER SYSTEMS IN CONTEXT HEAT RECOVERY



Heat- and grey water flow of Quooker PRO3 reservoir



Heat- and grey water flow of Quooker COMBI reservoir



Heat- and grey water flow of Quooker COMBI+ reservoir

A6: FLOW RATE

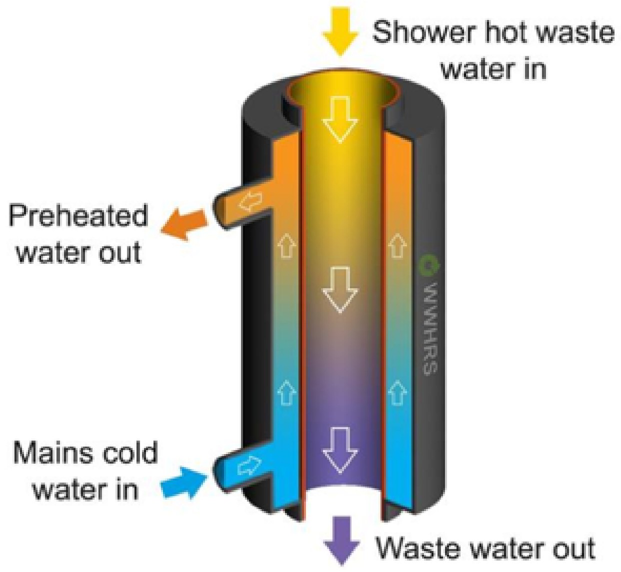
Flow Rate

```
> restart;
> t := 13;
  V := 2.5;
                                        t := 13
                                        V := 2.5
> Q := V/t;
                                        Q := 0.1923076923
```

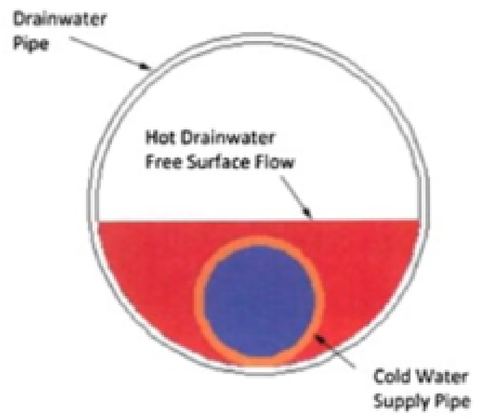
A7: CASE STUDIES

Vertical shower heat recovery systems are, compared to a horizontal shower heat recovery system, less expensive to purchase and more efficient. A vertical heat recovery shower system costs around €800 and a horizontal system costs between €2000 and €2600, depending on the placement of the system (Milieu Centraal, n.d.).

The working principles of both the vertical and the horizontal shower systems are similar to a shell and tube heat recovery system described in Chapter 4. Only the position of the water is different due to the horizontal or vertical placement of the pipe.

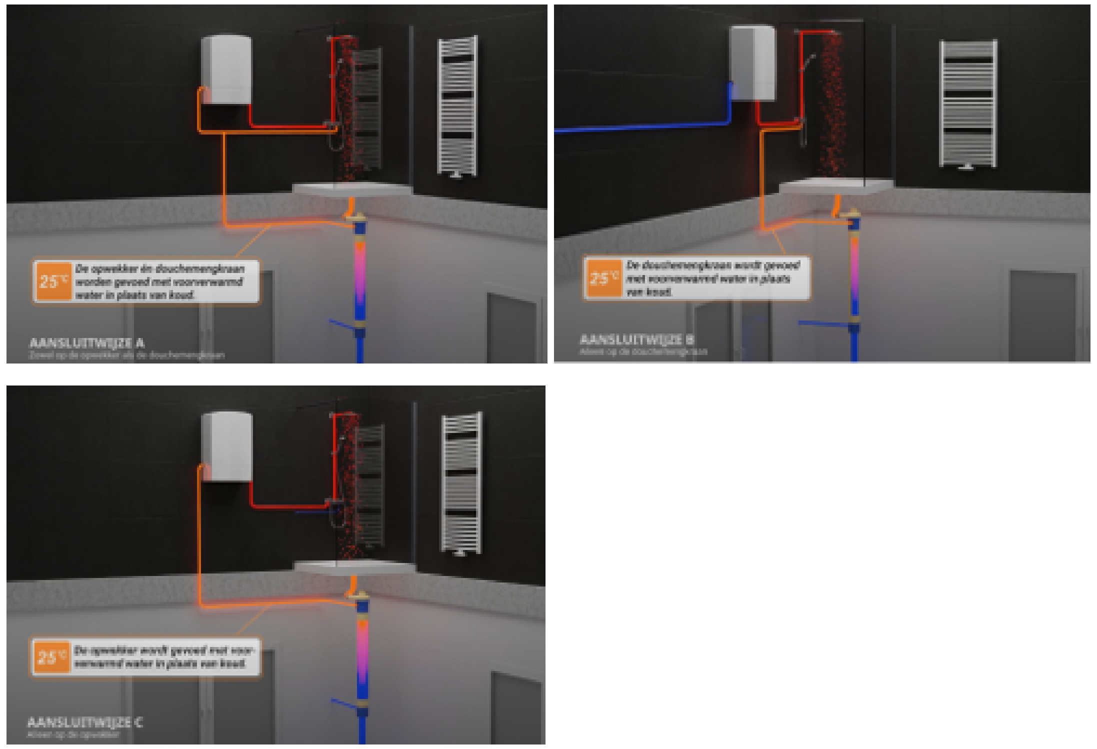


(Working principle horizontal shower heat recovery system (Operations Engineer, n.d.))



(Working principle horizontal shower heat recovery system (McNabola & Shields, 2013))

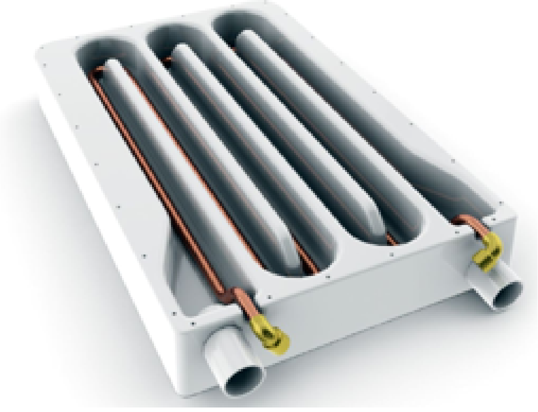
Vertical heat recovery showers have different options for its configuration. However, Configuration A in the figure below is most efficient (Technea, n.d.). Horizontal systems are usually less efficient than vertical systems, but not all homes allow vertical systems to work.



(Different compositions of a vertical shower heat recovery system (Technea, n.d.)

Milieu Centraal (n.d.) states that if the gas prices are 3 euros per m^3, the annual cost saving for a vertical system is €200 and for a horizontal system €160. Still, these numbers depend on shower behaviour, since the heat exchangers in these systems have to warm up before they reach their maximum efficiency rate. Therefore, these systems are only efficient for a relatively long period of time and thus a relatively large amount of water that water flows through the HEX system. A shower of 7.5 minutes can reach an efficiency rate of 40 to 50 percent, depending on the system and shower behaviour.

Horizontal heat recovery systems for showers are often placed in the shower tray and are more prone to fouling or clogging than vertical systems. The higher risk of fouling and clogging is a result of the laminar, slower flowing, grey water flow that runs through the system and a result of the corners and bends in the system where dirt and fat/oils can easily collect. This deposit often results in lower heat recovery efficiency rates, so cleaning is often needed. These systems are often cleanable by taking the lid of the system and using a cleaning brush to remove the deposit.



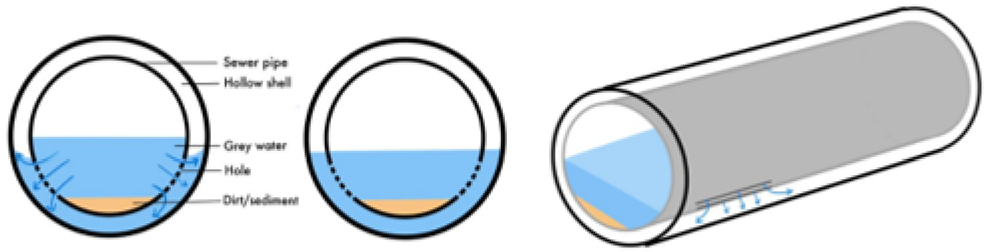
(Figure XX: Horizontal shower heat recovery system (Meanderhr, n.d.))

De warmte case study

DeWarmte is a company that sells a heat recovery system for the domestic sewer pipe. The sewer pipe in the crawl space of a home collects both greywater and blackwater in a pipe that has a higher diameter than the regular drain pipes in a house. The heat cycle system of DeWarmte claims to have no maintenance and claims to recover heat from the domestic sewer pipe through a heat exchanger with a passive filter, a heat pump and heat storage buffers. The patent of DeWarmte shows that HEX system of the Heat Cycle has the same working principle as a horizontal heat recovery shower and thus a shell and tube heat exchanger (Figure XX). However, a passive filter is attached to the HEX system (Figure XX).

(Figure XX: HEX system and passive filter system of the Heat Cycle (DeWarmte (n.d.))

The passive filter shown in Figure XX, uses the relatively slow flow of the water of the inner pipe to let the particles in the water sink through sedimentation. The relatively clean and warm water can enter the outer tube, without too much heat loss. After this water reaches the outer tube, the filtered water is brought to the buffer system, after which it is pumped in the heat pump of the Heat Cycle. The filter seems to clean itself by fresh water that can be flushed in the opposite direction of the filter direction. Sediment will slowly continue to move further through the inner sewer pipe into the city sewer system.



(Figure XX: Working principle of the passive filter of the Heat Cycle Wapperom, S. H., & de Vries, A. J. (2022))

A8: BRAINSTORM SESSION

BRAINSTORM SESSION GRADUATION PROJECT QUOOKER

Initial project brief from Quooker:

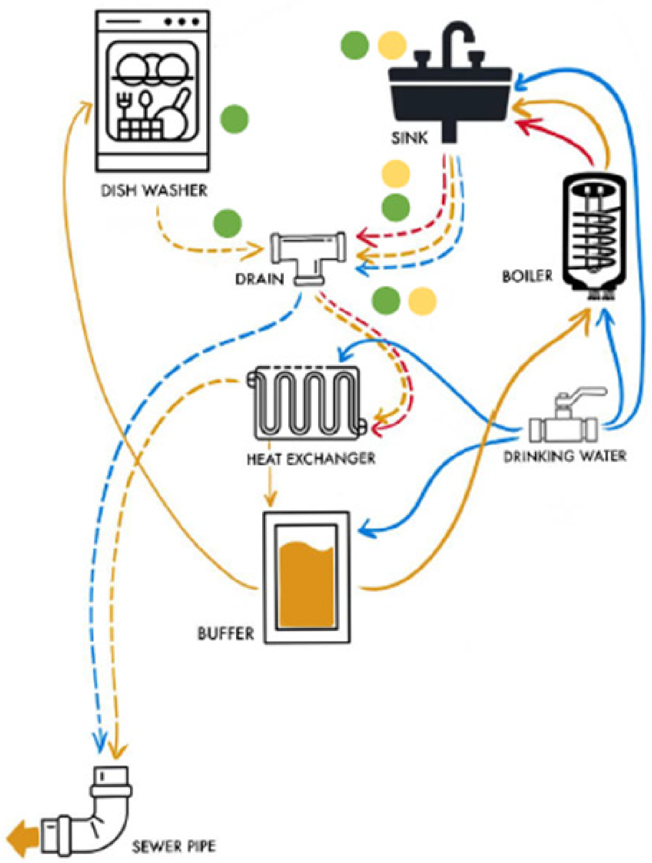
Is it possible to recover heat from hot/warm grey water that is drained through the kitchen sink after e.g. cooking.

Grey water

Grey water is domestic wastewater generated in households e.g. by the shower, dishwasher and sink with exception of toilet wastewater. This water includes e.g. dirt and fats.

My new design direction:

Is it possible to recover heat from grey hot/warm water coming from both the dish washer and the kitchen sink in such way that it has an economic and sustainable value for both Quooker and the end user?



How the system works

Figure 1 shows an example of how the grey water/drinking water can run through a potential heat recovering system.

Dashed arrow: grey water
Blue arrow: cold water
Orange arrow: warm water
Red arrow: hot water

The moment of using drinking water (tap or dish washer) is often not the same moment that warm/hot water is drained. Therefore, a buffer system is needed to keep the recovered heat warm until it is used for the dishwasher or is used to refill the boiler (figure 1).

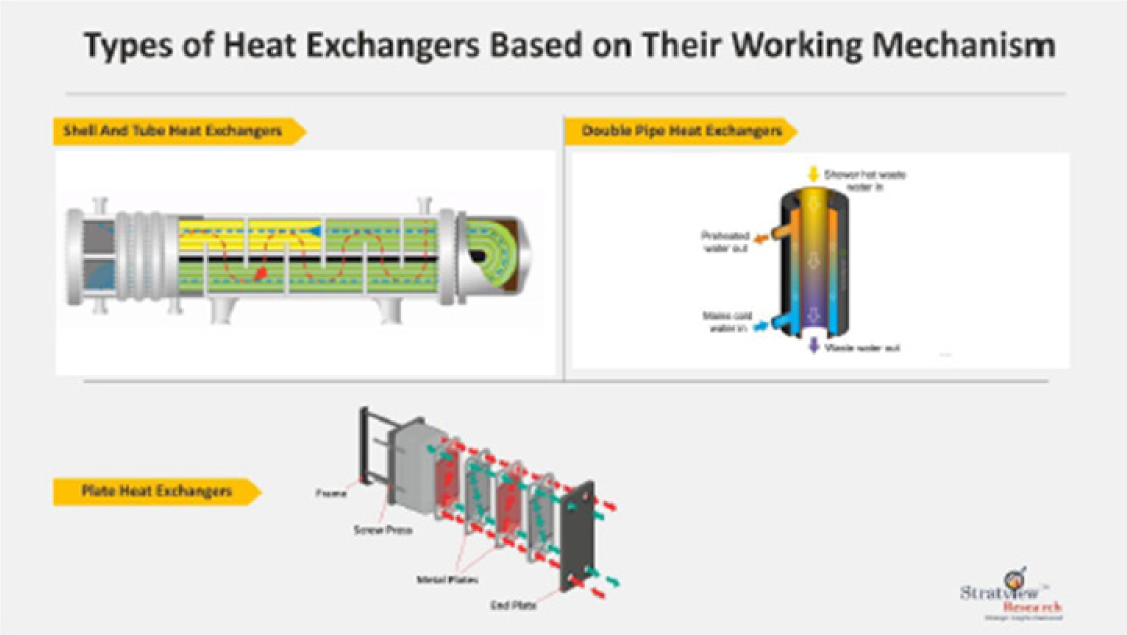
Furthermore, the water temperatures that are drained can differ and are not constant. Both hot water, medium warm water and cold water are flushed through the drain. Cold(er) water is not desired in the heat exchanger since it will have little to no effect on heating another stream/material.

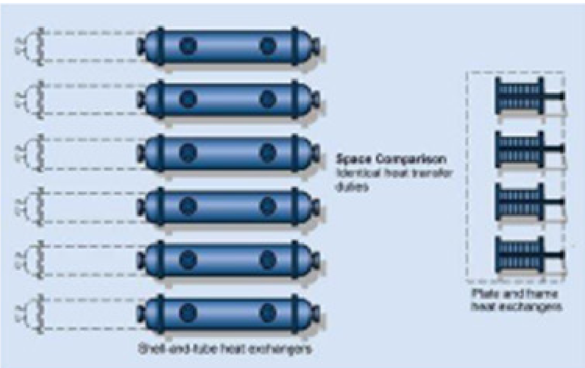
Figure 1: System example of heat recovery from drained water in the kitchen context

Lastly, the type of heat exchanger or specifications of the buffer are not defined in this image. This is something we may work on during the session 😊.

Heat exchangers

Heat exchangers are a way to exchange the heat from warm/hot water to a (cold) material. In the image below you can find examples of different types of heat exchangers and their working principle.





Size and efficiency (shell tube vs plate frame)

Shell & tube (price: medium)
- Lower risk fouling (particulates)
- Lower efficiency (up to 5x)

Plate frame (price: low)

- Up to 5x higher efficiency
- High risk of fouling (particulates)
- Modular in size & capacity

One of the main problems with heat exchangers is the risk of fouling by e.g. fats or dirt that runs through the system. This can for example occur as a result of sedimentation, scaling, corrosion, crystallization and biological growth. Sedimentation can be minimized by increasing the flowrate (velocity) of the fluid running through the heat exchanger.

Since this project is about recovering heat from grey water, chances of fouling of the heat exchanger are high.

Spots to make a change?

In figure 1 you can find both yellow and green dots. These are suggestions for where changes for certain challenges can be made.

- These dots show where grey water can potentially be pre filtered/cleaned before it reaches the heat exchanger.
- These dots show where cold water can potentially be channelled away into the sewer pipe before it reaches the heat exchanger.

A9: HEAT TRANSFER COEFFICIENT

> restart;
> $Ts := 290;$
$Tb := 350;$
$Tbin := 360;$
$d := 0.035;$
$L := 0.8;$
$mdot := 0.19;$
$mus := 11 \cdot 10^{-4};$
$mub := 3.79 \cdot 10^{-4};$
$Pr := 2.4;$
$k := 0.669;$
$cp := 4190;$

$Ts := 290$
$Tb := 350$
$Tbin := 360$
$d := 0.035$
$L := 0.8$
$mdot := 0.19$
$mus := \frac{11}{10000}$
$mub := 0.0003790000000$
$Pr := 2.4$
$k := 0.669$
$cp := 4190$

> #Tube cross−sectional area and the Reynolds number:

$$Ac := \frac{\text{Pi}\, d^2}{4};$$
$$Red := \frac{\left(\frac{mdot}{Ac}\right) d}{mub}$$

$Ac := 0.0009621127502$
$Red := 18237.12879$

> #Since Re <2300, the flow is laminar. Therefore the following equation applies for the corresponding average Nusselt number for a tube of length L:

$$Nud := 3.66 + \frac{0.065\left(\frac{d}{L}\right) Red\ Pr}{1 + 0.04\left(\left(\frac{d}{L}\right) \cdot Red\ Pr\right)^{\frac{2}{3}}};$$

$Nud := 21.02401322$

> #correction of variables (Table A8 from basic heat and mass transfer book)

$$cor := \left(\frac{mus}{mub}\right)^{-0.11};$$

$cor := 0.8893999849$

> #Corrected Nusselt number.
$Nudcor := Nud \cdot cor;$

$Nudcor := 18.69875704$

> #convective heat transfer coefficient

$$hc := \left(\frac{k}{d}\right) \cdot Nudcor;$$

$hc := 357.4133845$

> #With a constant shell temperature the following equation applies:

$$Tbout := Ts - (Ts - Tbin) * \exp\left(-\frac{hc \cdot 2 \cdot \text{Pi} \cdot 0.5 \cdot d\ L}{mdot \cdot cp}\right);$$

$Tbout := 357.2894231$

A10: PROTOTYPING PICTURES

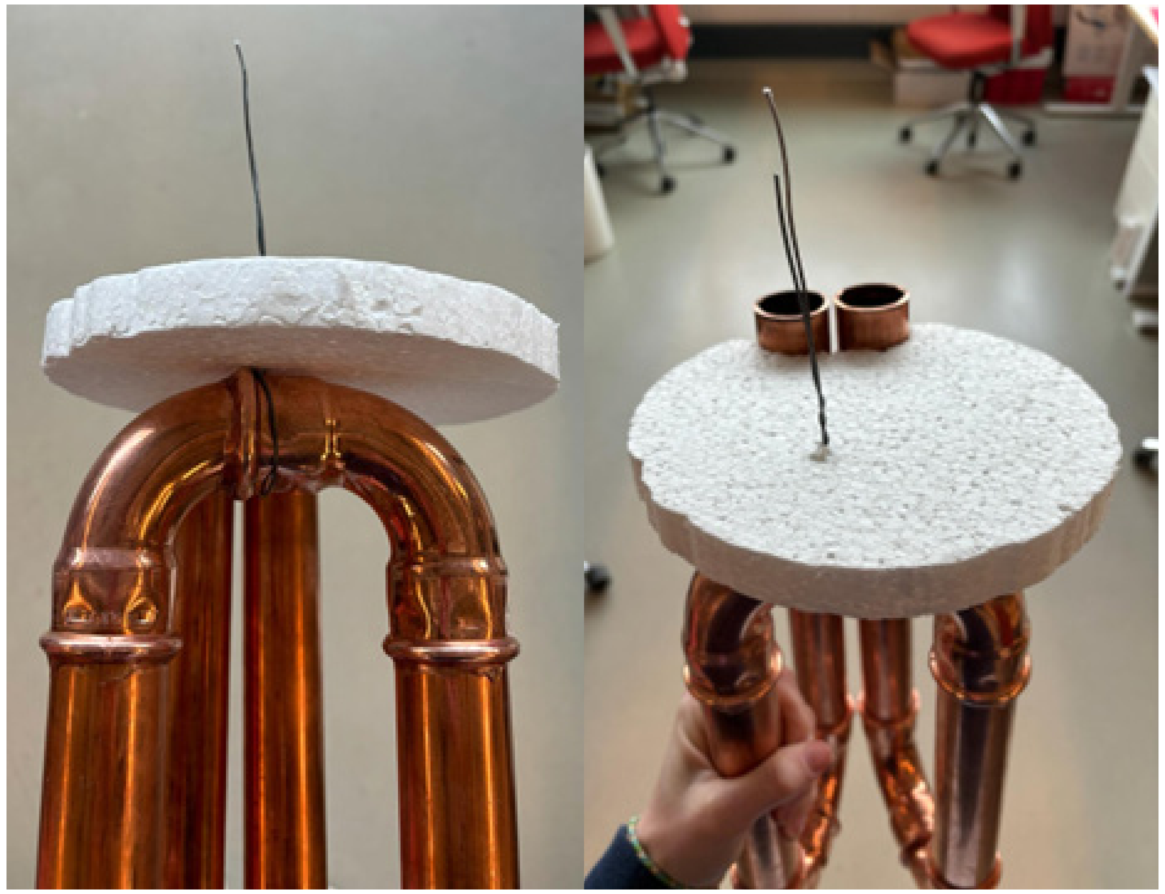
Arrival copper tube

Cutting the tube and bends into desired dimensions

Configuration of the tubes & quick calculations:

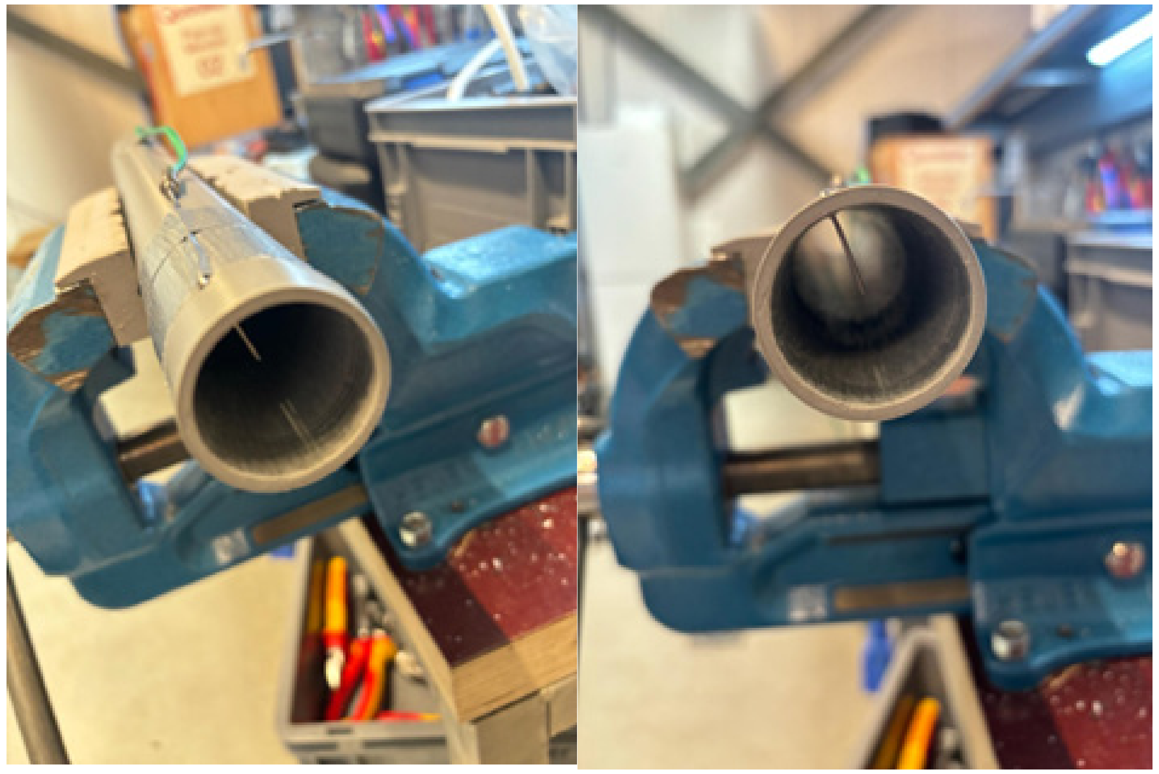
Shaping & thermoforming PVC tube (diameter 40 mm) around copper tube (diameter 35 mm)

Attaching the bends and straight tube parts with a jaw press:



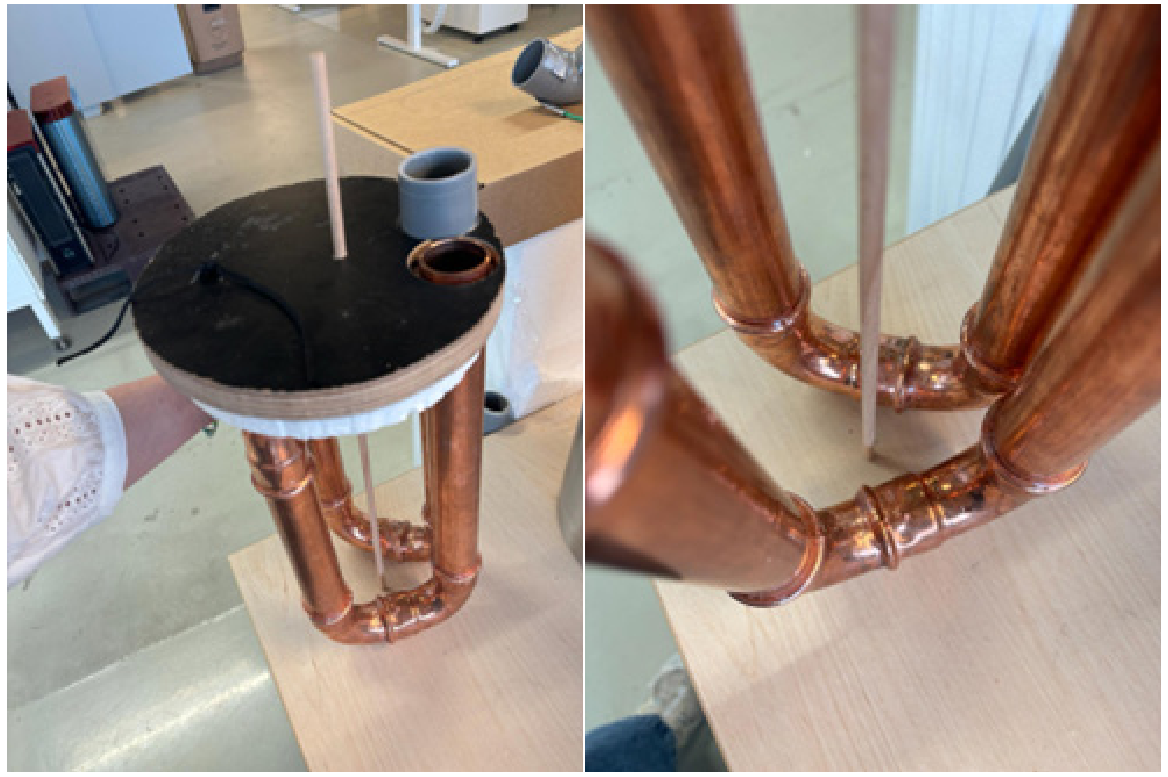
Attaching insulating material (PS) and wire to carry the weight of the W-shaped tube to the prototype:

Making a wooden lid with counterbored holes:



Glueing thermocouples to inlet and outlet of the HEX tube:

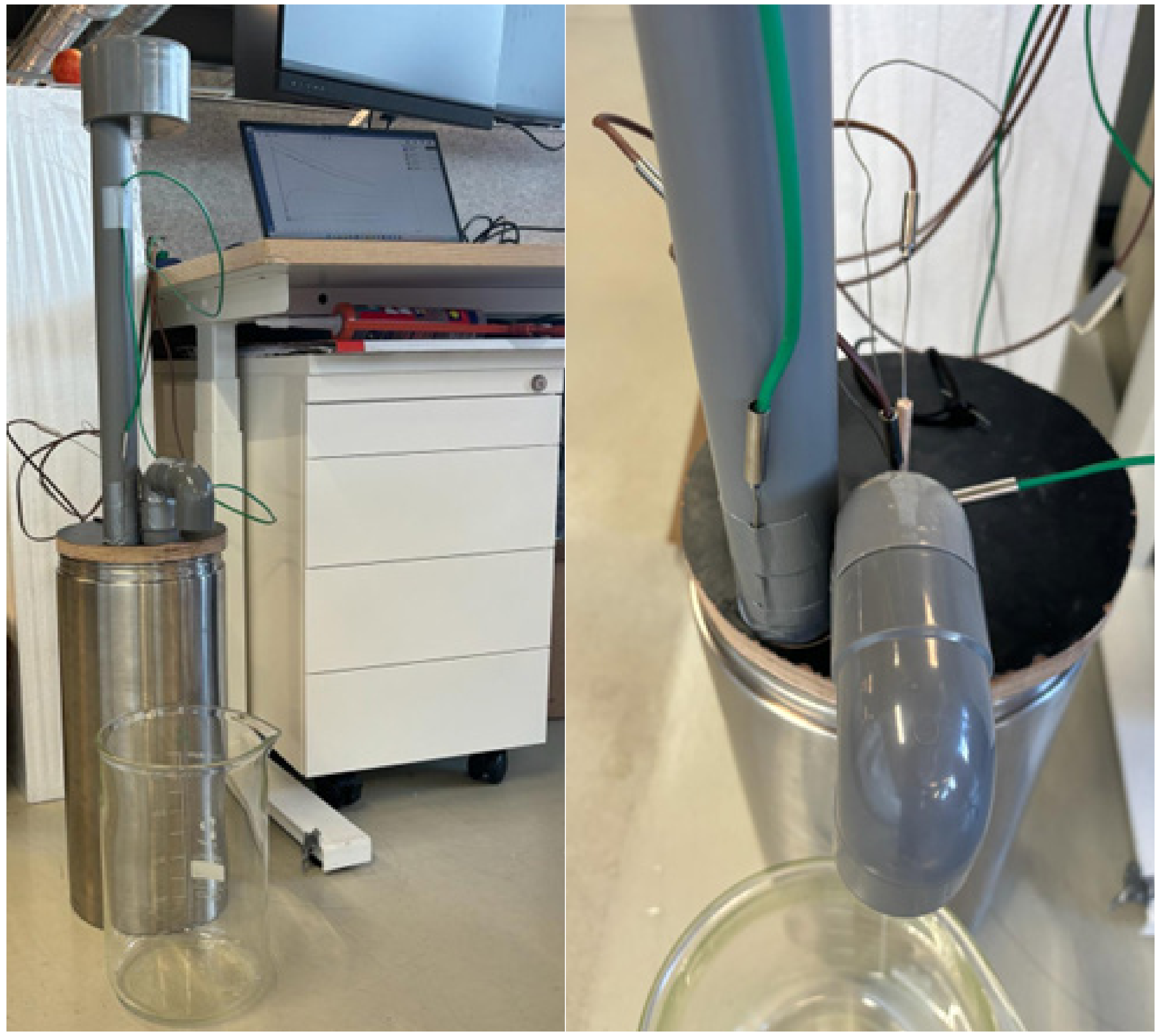
Wooden placeholder attached in the lid with HEX system:



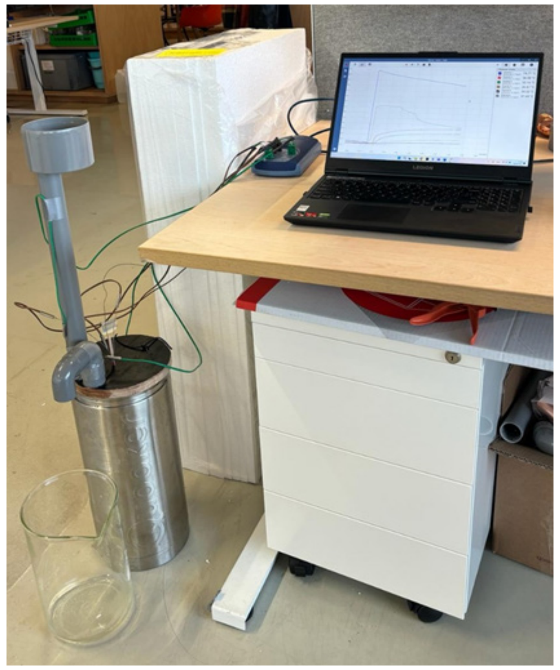
Making tight fitting holes for the wooden placeholder and thermocouples:

Placing thermocouples in the prototype on 1, 2,4 & 6 L depth:

Filling the buffer reservoir with the desired amount of cold tap water:



Filling the buffer reservoir with the desired amount of cold tap water:



Running a 12 h pilot temperature test:

A11: (AVERAGE) HEAT DISTRIBUTION BUFFER RESERVOIR

		T U-shape (°C)	T W-shape (°C)	Delta T (Avg W-Avg U)
Peak 1L	1L	48.00	47.00	
	2L	41.00	42.00	
	4L	30.00	34.00	
	6L	25.00	28.00	
	Avg 4L	37.25	39.25	2.00
	Avg 6L	33.17	35.50	2.33
Peak 2L	1L	47.00	47.00	
	2L	41.00	42.00	
	4L	32.00	34.00	
	6L	26.00	28.00	
	Avg 4L	38.00	39.25	1.25
	Avg 6L	34.00	35.50	1.50
Peak 4L	1L	38.00	40.00	
	2L	37.00	38.00	
	4L	33.00	36.00	
	6L	29.00	33.00	
	Avg 4L	35.25	37.50	2.25
	Avg 6L	33.17	36.00	2.83
Peak 6L	1L	33.00	36.00	
	2L	33.00	36.00	
	4L	32.00	35.00	
	6L	32.00	35.00	
	Avg 4L	32.50	35.50	3.00
	Avg 6L	32.33	35.33	3.00

A12: HEATING UP 4 & 6 L 3 DEGREES

U shape 4L max delta T = 3

```
> restart;
> #Lifespan [years]
  Lifespan := 10;
  #Water [L]
  Waterperday := 4;
  #Temperature [°C}
  TQuooker := 110;
  THexU := 32.5;
  #specific heat water [J/°C/kg]
  c := 4180;
  days := 365;
  CO2kgeqperKWh := 0.513;
```

$$Lifespan := 10$$
$$Waterperday := 4$$
$$TQuooker := 110$$
$$THexU := 32.5$$
$$c := 4180$$
$$days := 365$$
$$CO2kgeqperKWh := 0.513$$

```
> Totalwaterusage := Lifespan·days·Waterperday;
  Totalwaterusage;
```

$$Totalwaterusage := 14600$$
$$14600$$

```
> Qquooker := Totalwaterusage·c·(TQuooker− THexU);
```

$$Qquooker := 4.729670000 \times 10^{9}$$

> $KWhQuooker := \frac{1}{3.6 \cdot 10^{6}} \cdot Qquooker;$
> $CostQuooker := KWhQuooker \cdot 0.38;$

$$KWhQuooker := 1313.797222$$
$$CostQuooker := 499.2429444$$

$$CostQuooker := 499.2429444$$

```
> CarbonfootprintQuooker := CO2kgeqperKWh·KWhQuooker;
```

$$CarbonfootprintQuooker := 673.9779749$$

```
>
```

W shape 4 L max Delta T = 3

```
>
> restart;
>
> #Lifespan [years]
  Lifespan := 10;
  #Water [L]
  Waterperday := 4;
  #Temperature [°C}
  TQuooker := 110;
  THexW := 35.5;
  #specific heat water [J/°C/kg]
  c := 4180;
  days := 365;
  CO2kgeqperKWh := 0.513;
```

$$Lifespan := 10$$
$$Waterperday := 4$$
$$TQuooker := 110$$
$$THexW := 35.5$$
$$c := 4180$$
$$days := 365$$
$$CO2kgeqperKWh := 0.513$$

```
> Totalwaterusage := Lifespan·days·Waterperday;
  Totalwaterusage;
```

$$Totalwaterusage := 14600$$
$$14600$$

```
> Qquooker := Totalwaterusage·c·(TQuooker − THexW);
```

```
> Totalwaterusage := Lifespan·days·Waterperday;
  Totalwaterusage;
```

$$Totalwaterusage := 14600$$
$$14600$$

```
> Qquooker := Totalwaterusage·c·(TQuooker − THexW);
```

$$Qquooker := 4.546586000 \times 10^{9}$$

> $KWhQuooker := \frac{1}{3.6 \cdot 10^{6}} \cdot Qquooker;$
> $CostQuooker := KWhQuooker \cdot 0.38;$

$$KWhQuooker := 1262.940556$$
$$CostQuooker := 479.9174113$$

```
> CarbonfootprintQuooker := CO2kgeqperKWh·KWhQuooker;
```

$$CarbonfootprintQuooker := 647.8885052$$

```
> 499.2 − 479.9
```

$$19.3$$

U shape 6L Delta T max = 3

```
> restart;
  #Lifespan [years]
  Lifespan := 10;
  #Water [L]
  Waterperday := 6;
  #Temperature [°C]
  TQuooker := 110;
  THexU6 := 32.33;
  #specific heat water [J/°C/kg]
  c := 4180;
  days := 365;
  CO2kgeqperKWh := 0.513;
```

Lifespan := 10

Lifespan := 10
Waterperday := 6
TQuooker := 110
THexU6 := 32.33
c := 4180
days := 365
CO2kgeqperKWh := 0.513

```
> Totalwaterusage := Lifespan·days·Waterperday;
  Totalwaterusage;
```

Totalwaterusage := 21900
21900

```
> Qquooker := Totalwaterusage·c·(TQuooker − THexU6);
```

$Qquooker := 7.110067140 \times 10^{9}$

$$> KWhQuooker := \frac{1}{3.6 \cdot 10^{6}} \cdot Qquooker;$$

```
  CostQuooker := KWhQuooker·0.38;
```

KWhQuooker := 1975.018650
CostQuooker := 750.5070870

```
> CarbonfootprintQuooker := CO2kgeqperKWh·KWhQuooker;
```

CarbonfootprintQuooker := 1013.184567

\>
\>
\>

W shape 6L Delta T = 3

```
>
> restart;
  #Lifespan [years]
  Lifespan := 10;
  #Water [L]
  Waterperday := 6;
  #Temperature [°C]
  TQuooker := 110;
  THexW6 := 35.33;
  #specific heat water [J/°C/kg]
  c := 4180;
  days := 365;
  CO2kgeqperKWh := 0.513;
```

Lifespan := 10
Waterperday := 6
TQuooker := 110
THexW6 := 35.33
c := 4180
days := 365
CO2kgeqperKWh := 0.513

```
> Totalwaterusage := Lifespan·days·Waterperday;
  Totalwaterusage;
```

Totalwaterusage := 21900
21900

```
> Qquooker := Totalwaterusage·c·(TQuooker − THexW6);
```

$Qquooker := 6.835441140 \times 10^{9}$

$$> KWhQuooker := \frac{1}{3.6 \cdot 10^{6}} \cdot Qquooker;$$

```
  CostQuooker := KWhQuooker·0.38;
```

KWhQuooker := 1898.733650
CostQuooker := 721.5187870

```
> CarbonfootprintQuooker := CO2kgeqperKWh·KWhQuooker;
```

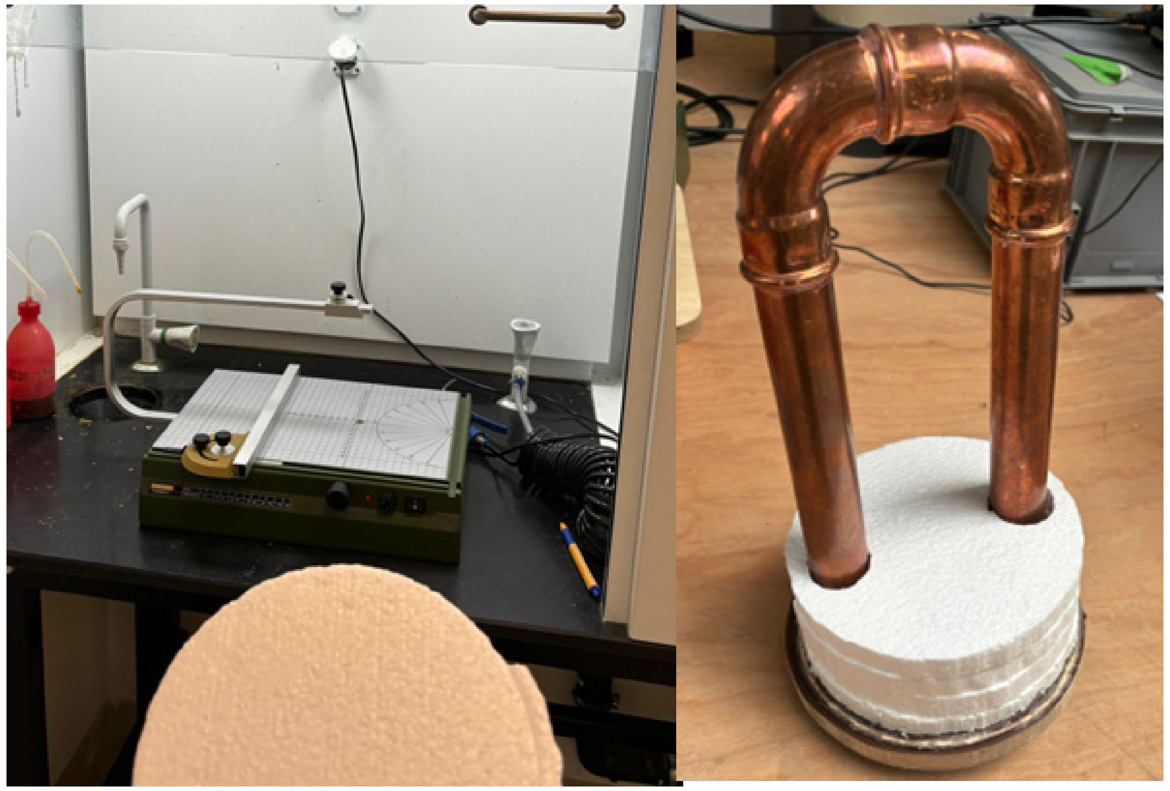
CarbonfootprintQuooker := 974.0503624

\>
\>
750.5 − 721.5

A13: PROTOTYPE TO FINAL CONCEPT PICTURES

Drilling 10 mm holes for the cold water inlet and outlet of the buffer reservoir.

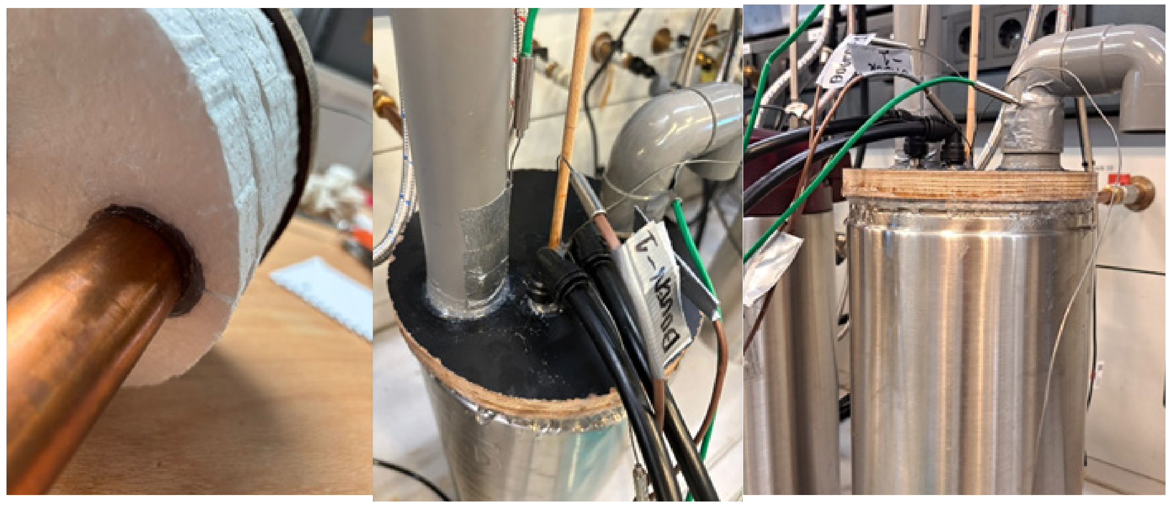
Making a rough surface on the lid so that the glue will better adhere to the surface.



Polystyrene layers were cut and attached to the lid so that the water volume in the buffer reservoir will not exceed 7L.

cold water inlet and outlet pipes were cut into the desired length of 115mm for the inlet and 415 mm for the outlet pipe. Then, creating a scratch on the outer surface of the stainless steel pipes so that the push-in fitting is securely attached to the pipes. On the other side of the push-in fittings, 10 mm LLDPE flexible pipes are attached.

Four thermocouples are attached with tie wraps and glue to the placeholder stick in the buffer reservoir (1L, 2L, 4L & 6L depth in the reservoir).



he tubes and lid were made waterproof by filling the gaps with kit and glue. Afterwards the prototype was left to dry for 24 hours.

An additional layer of duct tape and a strap was added around the lid of the prototype to limit the chance of water leakage during the final test. The inlet tube was attached to a needle valve and attached to the cold water net through a screw-in coupling.

A14: OUTCOMES FINAL TEST

Tap	T water (°C)	ΔT start (°C)
#1	36.3	8.7
#2	27.5	4.5
#3	28.2	5.2
#4	27.3	4.3
#5	29.2	6.2

Temperature tapped water:

#1-4 = measured temperature of water after tapping 4.5 L water in final test
#5 = average temperature of 6 L of water of best moment of tapping (see next table)

Peak	line	T U-shape (°C)
Peak 1L	1L	35.50
	2L	32.00
	4L	27.50
	6L	25.50
	Avg 4L	30.63
	Avg 6L	28.92
Peak 2L	1L	34.50
	2L	32.50
	4L	28.00
	6L	26.00
	Avg 4L	30.75
	Avg 6L	29.17
Peak 4L	1L	31.00
	2L	30.50
	4L	29.00
	6L	27.50
	Avg 4L	29.88
	Avg 6L	29.08
Peak 6L	1L	30.50
	2L	30.00
	4L	29.50
	6L	27.00
	Avg 4L	29.88
	Avg 6L	28.92

Estimation of average temperature of 4 and 6 L of water in the buffer tank at each peak, based on the temperatures of each water level at each peak:

A15: CALCULATIONS FINAL TEST

Outcomes final test reduction 10 years

```
> restart;
> #Lifespan [years]
  Lifespan := 10;
  #Water [L]
  Waterperdaydw := 4.5;
  Waterperdayafter := 6;
  #Temperature [°C}
  deltaTBuffer1 := 13.3;
  deltaTBuffer2 := 4.5;
  deltaTBuffer3 := 5.2;
  deltaTBuffer4 := 4.3;
  deltaTBuffer5 := 6.2;
  #specific heat water [J/°C/kg]
  c := 4180;
  days := 365;
  CO2kgeqperKWh := 0.513;

                    Lifespan := 10
                    Waterperdaydw := 4.5
                    Waterperdayafter := 6
                    deltaTBuffer1 := 13.3
                    deltaTBuffer2 := 4.5
                    deltaTBuffer3 := 5.2
                    deltaTBuffer4 := 4.3
                    deltaTBuffer5 := 6.2
                    c := 4180
                    days := 365
                    CO2kgeqperKWh := 0.513

> Totalwaterusagedw := Lifespan·days·Waterperdaydw;
  Totalwaterusageafter := Lifespan·days·Waterperdayafter

                    Totalwaterusagedw := 16425.0
                    Totalwaterusageafter := 21900

> Q := Totalwaterusagedw·c·(deltaTBuffer1) + Totalwaterusagedw·c·(deltaTBuffer2) + Totalwaterusagedw·c·(deltaTBuffer3)
     + Totalwaterusagedw·c·(deltaTBuffer4) + Totalwaterusageafter·c·(deltaTBuffer5);
                    Q := 2.441882850 × 10^9

> KWh := 1/(3.6·10^6)·Q;
  Cost := KWh·0.38;
                    KWh := 678.3007917
                    Cost := 257.7543008
```

```
> Carbonfootprint := CO2kgeqperKWh·KWh;
                                        Carbonfootprint := 347.9683061
>
```

Outcomes final test paybacktime

```
> restart;
> #Lifespan [years]
  Lifespan := 17.5;
  #Water [L]
  Waterperdaydw := 4.5;
  Waterperdayafter := 6;
  #Temperature [°C]
  deltaTBuffer1 := 13.3;
  deltaTBuffer2 := 4.5;
  deltaTBuffer3 := 5.2;
  deltaTBuffer4 := 4.3;
  deltaTBuffer5 := 6.2;
  #specific heat water [J/°C/kg]
  c := 4180;
  days := 365;
  CO2kgeqperKWh := 0.513;

                                        Lifespan := 17.5
                                        Waterperdaydw := 4.5
                                        Waterperdayafter := 6
                                        deltaTBuffer1 := 13.3
                                        deltaTBuffer2 := 4.5
                                        deltaTBuffer3 := 5.2
                                        deltaTBuffer4 := 4.3
                                        deltaTBuffer5 := 6.2
                                        c := 4180
                                        days := 365
                                        CO2kgeqperKWh := 0.513
> Totalwaterusagedw := Lifespan·days·Waterperdaydw;
  Totalwaterusageafter := Lifespan·days·Waterperdayafter

                                        Totalwaterusagedw := 28743.75
                                        Totalwaterusageafter := 38325.0
> Q := Totalwaterusagedw·c·(deltaTBuffer1) + Totalwaterusagedw·c·(deltaTBuffer2) + Totalwaterusagedw·c·(deltaTBuffer3)
     + Totalwaterusagedw·c·(deltaTBuffer4) + Totalwaterusageafter·c·(deltaTBuffer5);
                                        Q := 4.273294988 × 10^9
> KWh := 1/(3.6·10^6)·Q;
  Cost := KWh·0.38;
                                        KWh := 1187.026386
                                        Cost := 451.0700267
> Carbonfootprint := CO2kgeqperKWh·KWh;
                                        Carbonfootprint := 608.9445360
```


A16: COST PRICE

In consultation with a procurement expert at Quooker, and based on existing part prices of the Quooker COMBI(+) kettle, the cost price of the final concept was determined. Most part prices are based on the cost price of existing COMBI (+) parts. The cost price of the copper tube was based on material weight, the copper price per kg in May 2024 and on manufacturing costs:

1. Cap	€11.80
2. PVC outlet/inlet pipes (2x)	€0,65
3. Solenoid electronic valve with temperature sensor	€5,00
4. Water outlet buffer reservoir	€0,58
5. Cold water inlet buffer reservoir	€1,51
6. Temperature sensor	€0,90
7. PVC connection tubes (2x)	€0,92
8. Connection ring cap	€1,33
9. PS insulation layer	€1,78
10. Nuts (11x)	€0,48
11. Lid	€2,46
12. Stainless steel cover	€0,52
13. Rubber ring	€0,53
14. Copper HEX tube	€30,74
15. Buffer reservoir	€24,20
16. Pressure reducing valve	€0,00
Total	**€83,40**