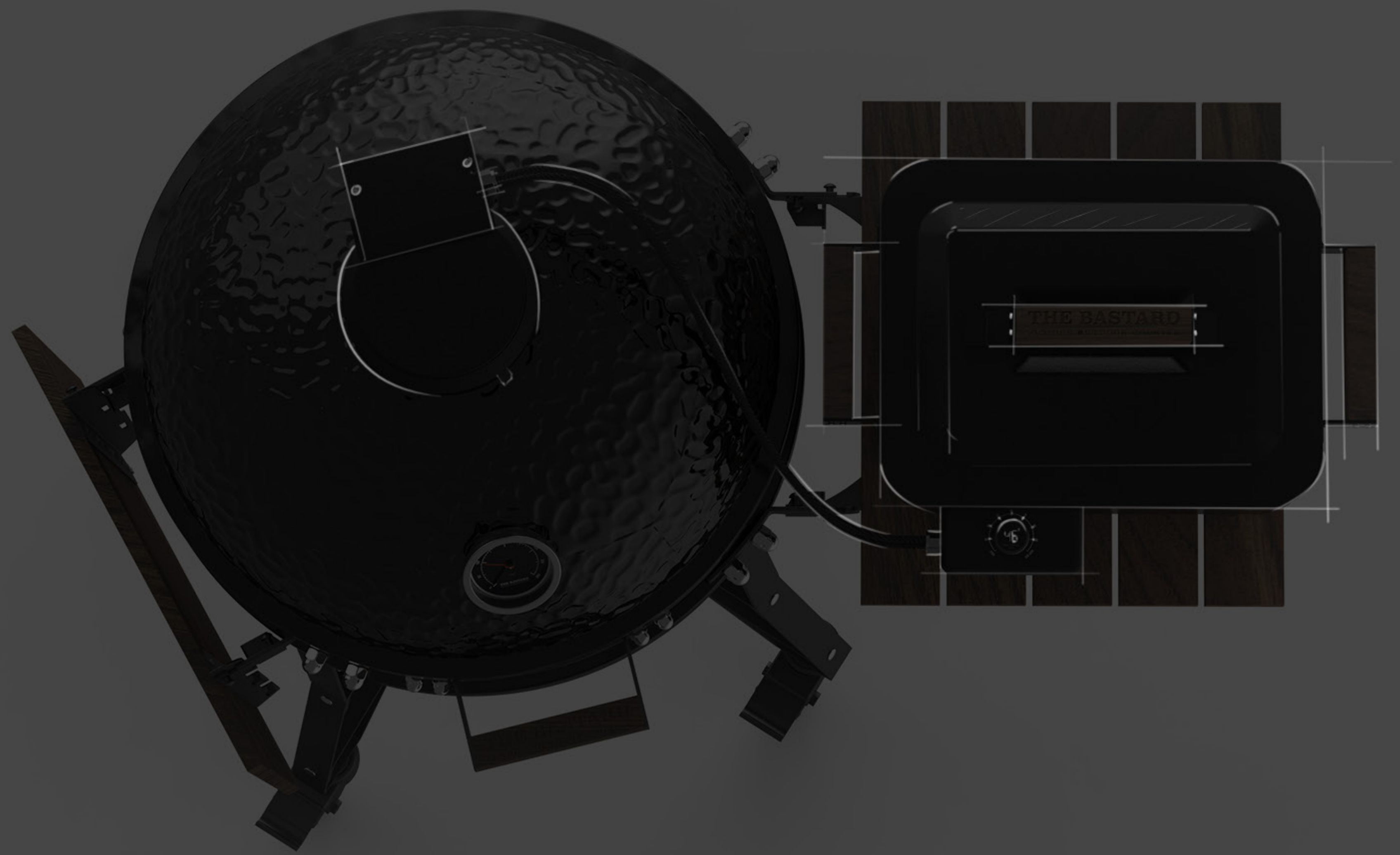
Using Residual Heat Of A Ceramic Barbecue To Power A Product

Graduation Report by Bart Leeuwenburg



Integrated Product Design
Industrial Design Engineering
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COLOPHON

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TU Delft chair: Ruud J.H.G. van Heur
TU Delft mentor: Stefan G. van de Geer
TU Delft second mentor: Ad E. Huisjes

Company coach: Bobby M. Adriaansens
Project executed for: 200 Fahrenheit

This project started with Stefan van de Geer as main responsible chair, Ruud van Heur as project mentor and Bobby Adriaansens as the company mentor. However due to unfortunate circumstances, Stefan had to quit the graduation team a few months after the project started. This is when the graduation team changed to its final form; Ruud van Heur took on the role as project chair and Ad Huisjes joined the team as the project mentor.

I want to thank all of them for their expertise and support throughout the project.

/ABSTRACT

Context

In a society where sustainability is becoming more and more relevant, coal-burning kamado barbecues are more popular than ever in the Netherlands. From an ignited barbecue a significant amount of energy is lost through heated air. This brings up an interesting design opportunity; "Is it possible to design a product which proposes a more efficient use of the energy of a kamado barbecue?"
This project investigates the possibility to design a product powered by energy lost during the process of a barbecue. It has been executed for the company 200Fahrenheit, a relatively young company that is specialised in ceramic barbecues known as kamados. The company is growing rapidly and where most competitors seem to barely change, the company is eager to invest in innovative products and sustainability in general to stay relevant in the future.

Approach

The foundation of the process was the classic double diamond design approach, consisting of Research & Analysis, Conceptualisation, Embodiment and Final Product. The outcome of the Research & Analysis phase brought valuable insights from extensive desk research to qualitative interviews with users and vendors. It led to a defined persona with valuable needs, preferences and frustrations. From the embodiment part of the process, the aim was to deliver answers to the high risk/high reward assumptions. The emphasis lied on the functionality and feasibility of the implemented technology, which was crucial for the company to know whether or not it was fruitful to continue developing. Research by design, design by doing and prototyping proved to give insights in a time efficient manner.

Result

The result of the project is a product that is able to keep food warm in a container at the right temperature after it has been grilled. The temperature of the container can be set to match the needs of the user. It was found that most heat energy was lost via the chimney of the kamado, which made this a suitable location to harvest energy. The energy that powers the product is completely recovered from the hot air that exits the kamado when it is ignited, in the form of heat energy collected by water. The water transfers the heat to the container, warming up the container. The electricity used by the system is generated by this residual heat as well using Peltier elements. Peltier elements are small electronic plates that are able to convert a temperature difference to electricity. This temperature difference is provided by the water which is always under 100 degrees Celsius, and the outgoing air of the kamado which when ignited, virtually always exceeds 100 degrees Celsius.
The product empowers the user to take advantage of the normally wasted energy. Where kamado users were already putting an incredible amount of effort in their dishes, the product now enhances their dish until the last moment where it is presented to the table, under perfect conditions.

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/INTRODUCTION

At the moment of writing, a crushing report of the Intergovernmental Panel on Climate Change (IPCC) once again highlights the importance of changing to a more sustainable society. This can be hard to rhyme with the thousands of barbecues that are lit in the Netherlands as soon as the first sunrays introduce summer. While doing my internship at the company 200Fahrenheit, I asked myself how their barbecues could be more sustainable, or at least more efficient with their energy. Anyone that has stood beside a barbecue has felt the incredible amount of heat that is lost to the surrounding air. Heat that as of now has no purpose. This is the driving force behind this thesis and our main research question: This is where the main research question arises which is the driving force behind this thesis;

"Is it possible to design a product which proposes a more efficient use of the energy of a kamado barbecue?"

The project is executed for the company 200Fahrenheit, which specializes in ceramic kamado barbecues. It seems that users of a kamado are willing to put an incredible amount of time and effort in their dishes, which can take up to a full day to properly prepare. Only little technology is present in the kamado ritual today. This ritual of the barbecue is very important to most users and designing a product, it should be kept in mind that this ritual cannot be affected negatively in any way, which proposes a challenging design assignment. At the same time, the implementation of recapturing heat will be challenging for me as an industrial designer that has limited prior knowledge about electronics and thermodynamics. These challenges will run like a thread through this project and lead to a unique and self-sustaining product which introduces a little sustainability to the kamado barbecue.
How these challenges are tackled will be further highlighted under Approach.

Approach

For this project, the classic double diamond design approach is used as a foundation. This approach consists of four parts; discover, define, develop and deliver (UK Design Council, 2019) To suit it better to this project, it was renamed to Research & Analysis, Conceptualisation, Embodiment and Finalizing the design. A visualisation of the double diamond approach is shown in figure 1.
The outcome of the Research and Analysis phase brought many valuable insights from extensive desk research about culture and trends, as well as from qualitative interviews with users and sellers of kamado barbecues. The outcome was a defined persona with clear needs, preferences and frustrations. Experiments about the heat energy of a kamado were done which gave promising results, thereby giving the confidence to continue the project in the same direction.
The next phase was Conceptualisation, which was chosen to be relatively short. This choice was made because the Embodiment phase was more significant to the company.
Where the first diamond was mainly focused on exploration and was rather open-ended, the embodiment part was done with a different approach. The aim was to deliver answers to the high risk/high reward assumptions. The emphasis lied on the functionality and feasibility of the implemented technology, which was crucial for the company to know whether or not it was fruitful to continue developing. With 3D printing, electronics and a kamado barbecue available at home, it allowed for a practical and effective research by design and design by doing approach which gave many insights in a time efficient manner, despite the restrictions posed by the COVID-19 pandemic.

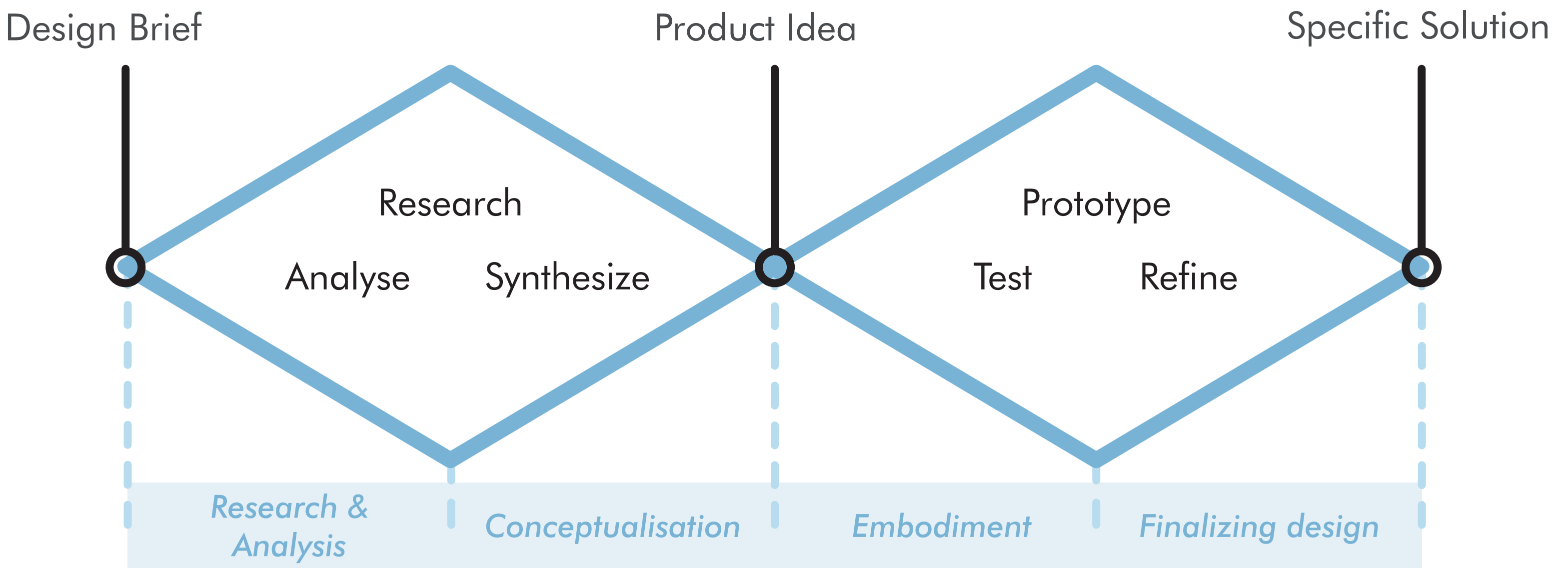


Figure 1. Visualisation of the double diamond approach

Research & Analysis

To be able to design a feasible, viable and desirable product, first the context needs to be fully understood and potential opportunities need to be highlighted. In this phase, knowledge is gathered about the context of a kamado, a study was conducted starting with a brief analysis of the company, its brands, goals and opportunities. Then, a short study is presented on the history of the kamado and about current barbecue cultures. From that point, explorations were done on trends, qualitative interviews with different kamado users to end up with justified personas. Lastly, the kamado barbecue is analysed from a more technical approach, learning about the heat transfer principles and determining heat loss at critical or promising locations.
This phase will end with a fertile set of insights and opportunities, which will bring us to the Conceptualisation phase.

Figure 2. Interviewee checking the status of his GrillGuru kamado

/ABOUT THE COMPANY

This project has been executed for 200 Fahrenheit, which is a Dutch company that mainly sells ceramic barbecues, also called kamados. Besides, they make different tools and accessories that come into play when having a barbecue. Although there are many competitors on the market that offer ceramic barbecues, the company is growing rapidly and practically taking over the Dutch market while only existing for about 8 years. The Covid-19 pandemic gave general interest in outdoor cooking a boost (Google Trends, 2021), which had a play in their revenue almost doubling last year.

The Bastard

The company owns multiple kamado brands that cover different segments of the market and have their own marketing plan. Their flagship of which is “the Bastard” which covers the higher end spectrum. To compare the brands, we will compare the prices of the large complete editions since these are sold most (200 Fahrenheit, 2020). For The Bastard, the large complete edition are sold at approximately 1399 (Bastard Classic) and 1499 (Bastard Urban) (Bol.com, 2021). The bastard is marketed with lots of “masculinity; in most marketing it is operated by a chef with a beard and lots of tattoos, while he is throwing whiskey on his sizeable piece of meat. The slogan of the Bastard is “serious outdoor cooking”, although you could say that they do not always take the word serious too serious. With on one hand the great range of tools and almost intimidating barbecues, they also make barbecue fun and accessible with for instance their own cooking books which they call “We Can(’t) BBQ” ironically.

Grizzly Grills

Furthermore, the company sells Grizzly Grills which is slightly less expensive, and is sold for around 999 euros for a large complete kamado. Grizzly Grills aims for the more adventurous user; as it states on the website of chain store Welkoop: “Welcome to the world of Grizzly Grills, the freedom of adventurous enjoying.” (Welkoop, 2021). Grizzly Grills is the least selling brand of 200 Fahrenheit and generally, less effort is put into the marketing of it mainly because of the lack of resources to do so.

Figure 3. A photo from the front page of Grizzly Grills on Facebook, referring to nature. (Facebook, 2021)
Figure 4. How The Bastard is marketed often; beards, smoke and tattoos (200 Fahrenheit, 2020)
Figure 5. The brand communicates that everybody is welcome at GrillGuru (GrillGuru, 2021)

Grill Guru

Lastly we have Grill Guru; “Outdoor Cooking The Easy Way”. A large complete priced at 649 euros at the hardware store Hornbach, it is the least expensive kamado they offer which aims for the middle segment of the market. It is marketed as the kamado for everyone, with pictures of happy people eating together. In the year 2020 and 2021 they collaborated with the supermarket chain Albert Heijn, which drastically increased sales and brand awareness in the Netherlands. (Antal, 2021)

The Goal Of The Company

200 Fahrenheit is eager to invest significantly in their brands to stay relevant in the future, especially in their flagship The Bastard. They have been expanding their research and development department remarkably, from 1 to 3 designers in one year. By doing this, they hope to continuously bring new products to the market that are innovative.

The reason why there is such a need for innovation at the company, is because there has been little innovation in the kamado market for many years. This gives that every innovation they bring to the market puts them two steps ahead of their competition. During the project, they offer a vast freedom in design, as long as the result can convince them of its value. They also provide the opportunity to design for all brands or one in particular. They are interested in “sustainable” qualities of a product, but it is not a necessity to them. Finally, they want to know if the designed product in the proposed direction can be feasible, viable and desirable.

Figure 6. From left to right; the GrillGuru Large Classic, Grizzly Large Elite and The Bastard Large Classic

/BARBECUE CULTURE

A culture can be hard to grasp, and so is that of barbecue. In the following chapter differences in barbecue cultures between countries will be highlighted; especially that of the United States since its huge role in barbecue. Furthermore, general barbecue trends that are developing will be highlighted from trends in TV series, Instagram to why people keep loving cooking with fire so much.

Trend From The United States

Among the many ways to describe North American culture, barbecue is one of the classics. On the fourth of July, millions of Americans celebrate the independency of the United States and they do that by gathering their families for huge dinners. There, many typical United States low and slow dishes are enjoyed (Corte, 2020), cooked above huge pellet grills or home-made oil barrels, cut open and converted to a smoker. Generally, this is the conception of barbecue within the United States; indirect cooking or smoking meat which is done for long times, sometimes over 18 hours for one dish. This is in contrast with the rest of the world where barbecue is generally considered direct cooking, usually done above burning gas or coals. (Bawdon, 2018) However, as a sales manager from 200 Fahrenheit confirms, many US trends quickly find ground in Europe and so does low and slow barbecue (Antal, 2021).

Figure 7. A big smoker barbecue that is common in the US; often shaped like a cut-open oil barrel (Caldwell County bbq, 2020)

Masculinity In Barbecue

Grilling on a barbecue seems to be thought of as a masculine thing to do. As well as in the US (Jennings, 2019) as in the Netherlands, men are usually the one that control the grill (Hielkema & boomsma, 2020). In the Netherlands, mostly men would state that they control the grill most of the time, while women generally state that they most of the time do not. Vegetarian alternatives are barely gaining ground during barbecues today, with 13% in 2015 to 14% in 2020 of the prepared dishes being vegetarian. At 90% percent of the barbecues last year, meat is prepared (Hielkema & boomsma, 2020). It could be that eating meat is generally considered to be a manly thing, and that the high meat consumption during barbecues is explained by the fact that they are manned by men. Men tend to like meat more than women, women are about twice as like as men to say they are eating less meat compared to men in the US (Blumberg, 2020).

In the Netflix series “The American Barbecue Showdown” competitor mister Boatright is enjoying making the main meat dish while he is struggling to think of a side dish. He explains “My wife is great when it comes to sides. If she’d be here man, it would be all right” while he is struggling to turn the stove on. In the next shot one of the judges come in; “Most guys, you know, they do the barbecuin’, the wife does the inside, she does the sides, you know?” Kevin Bludso explains, as if it is factual. (Netflix, 2020)

The way this information is presented shows clearly how strong this gender stereotype is, at least in the US. Something worth noting is that this effect suddenly stops when we look at electric grills, since the Hearth, Patio and Barbecue Association found that 55% of electric grills are operated by women (Browning, 2014).

Working With Fire

As Jennings suggests, the "man controlling the grill" stigma might have something to do with fire in general, which brings a certain excitement and danger (Jennings, 2019). Fire has always been something special for people, from Darwin stating that it was the second greatest discovery by the human species (Darwin, 1871), to nowadays people loving to get together around a campfire. The Netflix series Chef's Table: BBQ shows a part of this trends that has been able to penetrate famous kitchens all over the world. Different ways of cooking with fire are described, from American barbecue, grilling virtually all known dishes above direct fire, to ancient Mayan traditions where they bury meat on a fire. (Gelb, 2020) But this attractiveness of fire is not limited to fancy restaurants. If we look at wok restaurants, there will be lines of people that are staring to the food that is being prepared, astonished by the big flames whelming around the stove.

A certain excitement and danger; the fire adds to the experience. And most of the time, the products around it all line up. In the wok restaurants, the chefs are throwing around with sauces and the food, while scraping their full metal spoon against the worn but everlasting wok pan. Lennox Hastie serves lettuce to people cooked in direct fire, branded by tracks of the blackened metal grill. And food memes receive loads of attention online, like Turkish chef Nusret Gökçe, dubbed "Salt Bae" who swings around with a metal blade which he uses to "suavely methodical" slice meat, dressed in only a white shirt and notable black sunglasses. Then he works to the moment that he throws the meat on the plate and famously sprinkles salt on the food via his forearm, giving him the nickname. One of his videos doing this ritual has over 17 million views (@nusr_et, 2017), which indicates the great interest.

Figure 8. "Salt Bae" performing his famous move (@nusr_et, 2017)

Conclusion

During a barbecue, people like to be excited about the experience and working with fire is an important factor in that. Barbecue trends from the United States tend to fly over to Dutch barbecue culture; people are willing to put more effort and time in their barbecue dishes. Lastly, men are the ones that control the grill today, and this is a stigma that will probably not change quickly in the coming decade. This is not the complete story though, because the wife usually plays an important role in the buying process. This will be further researched by interviewing vendors and users of kamados.

Figure 9. Sydney chef Lennox Hastie cooking on direct fire, touching the meat to check cooking progress (Gelb, 2020)

/GETTING TO KNOW THE USER

From general culture, we dive deeper into the actual user of the kamado. The following study was done to determine who uses the kamado, what types of users exist and which user the design should aim for. Existing studies were analysed and compared, qualitative interviews are conducted with users with different types of kamados and salesmen are interviewed, eventually wrapping it up in an overarching persona which can act as a guide during the rest of the design process. The goal is to ensure the end product is truly designed for the user.

Local Barbecue Trends

In The Netherlands, yearly over half a million Dutch customers are looking to buy a new barbecue. And if we take a look at the popularity of barbecues, the Netherlands ends up being at sixth place, right behind typical barbecue nations like Australia, New-Zealand, Canada, the United States and Singapore (Beslist BBQ Infographic, 2016). Furthermore, the Dutch national barbecue research gives us the following data from 2020, as shown in figure 10 (Hielkema & boomsma, 2020)

The study also shows that 1 out of 5 interviewees puts meat replacers on the barbecue occasionally. To many people (81%), being outside is an important factor in having a barbecue.

People indicate the following about what they think is the hardest part of having a barbecue;

Cleaning the barbecue after use (26%)
Buying the right amounts of groceries (24%)
Keeping the barbecue at the required temperature (20%)
Avoiding the meat to be burned (18%)
Making sure meats are well cooked (13%)
Lighting the fire (13%)
Cleaning the barbecue before use (12%)
Get the right fire at the right time (11%)
Start preparations in time (10%)
Marinate the meat right (5%)
(Hielkema & boomsma, 2020)

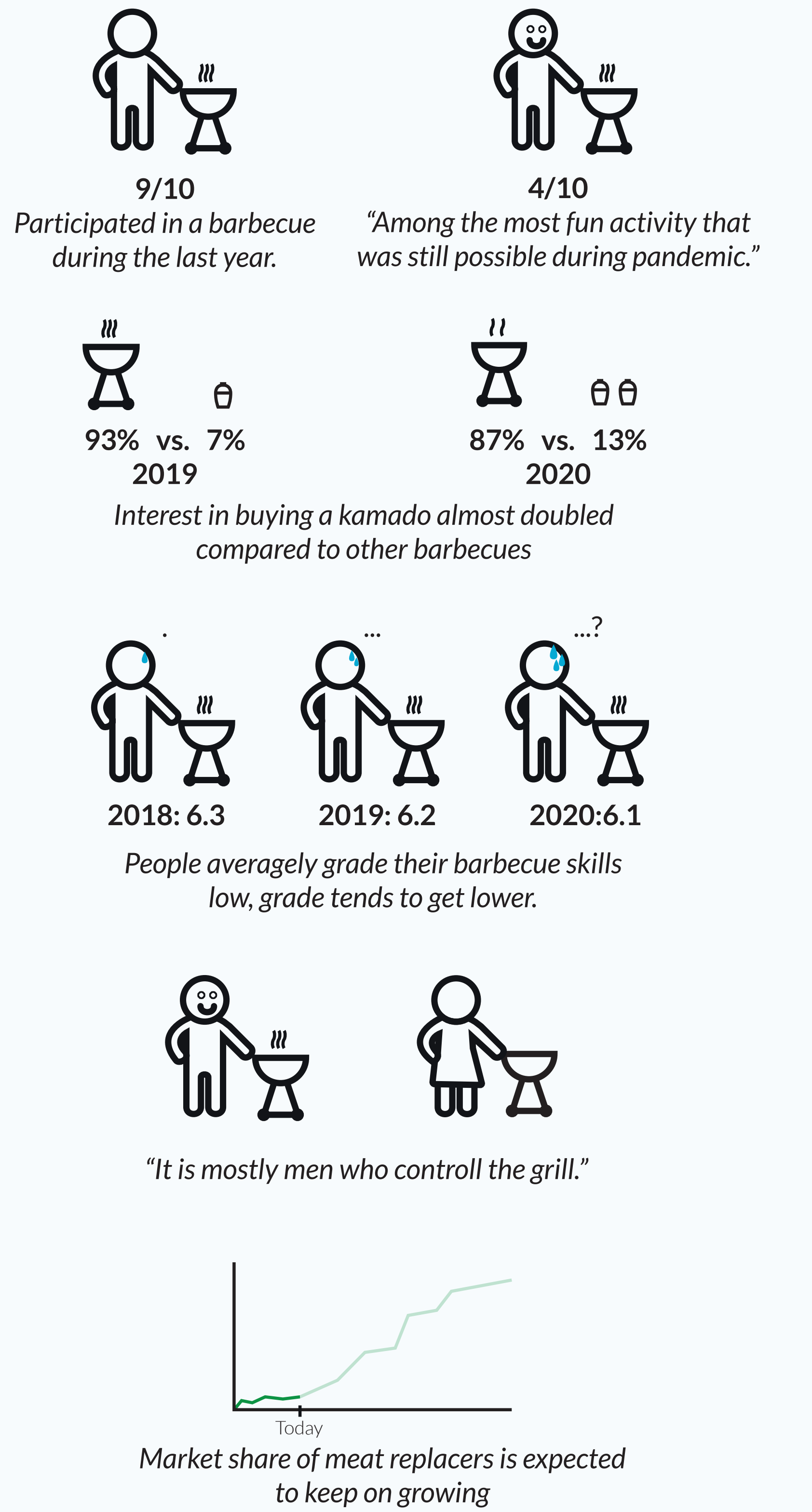


Figure 10. infographic on barbecue trends in the Netherlands.

Outdoor Cooking

Next to general barbecue trends, outdoor cooking has been and still is a significant trend. Especially during the global pandemic as an article states; "Outdoor cooking rising: trendy, corona proof and a true eye catcher" (Reijden, 2021). In May 2021, a full summer with corona restrictions had taken place, which has boosted the need of a convenient outdoor area at home. According to Google Trends at figure 11, if we compare 2019 and 2020 on general outdoor cooking terms "bbq" "garden" "cooking" and "outdoor" a significant increase in interest is observed.

This data suggests that the barbecue market would have exploded around that time as well, and for the company 200 Fahrenheit, it has. The total market share of 200 Fahrenheit between January to March has increased from 14.4% to 33,2% between 2020 and 2021 (GfK , 2021). As sales manager Antal explains; the company noticed that people often had to stay at home and cancel holiday plans (Antal, 2021). This meant that they had more money left to spend on other products. 200 Fahrenheit expects that this boosted their sales since their kamados are relatively expensive and high end products. Antal also points out that they were early with getting orders from market leading hardware stores, which meant that they could deliver the barbecues earlier than their competitors. They noticed that if the products are displayed in stores earlier in the year, there is a significant rise in sales as well. (Antal, 2021) They suggest that this combination of factors was crucial in the fact that Grill Guru products sold almost quadrupled between the first quartile of 2020 and 2021; 21,6% to 74,2% (GfK , 2021).

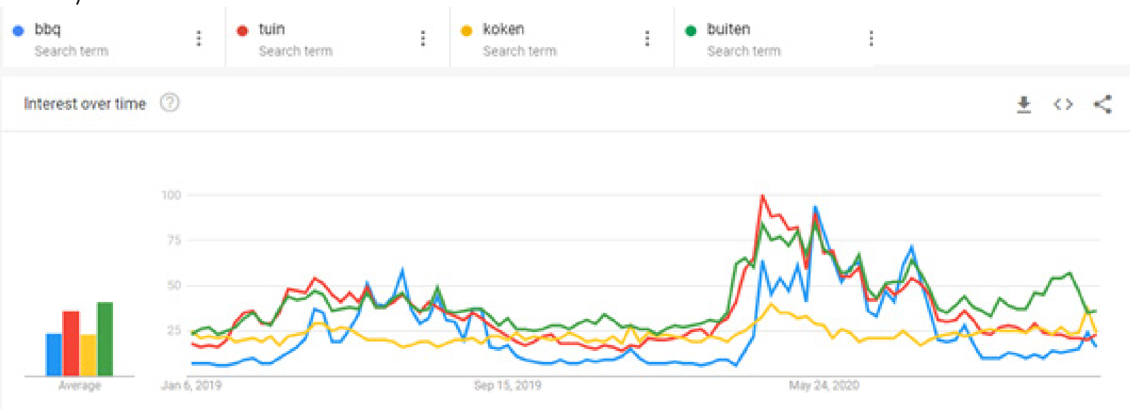


Figure 11. Google trends on the terms bbq, garden, cooking and outdoor (Google Trends, 2021)

Another signal of the great interest in outdoor cooking today can be found in both Facebook groups "The Bastard Owner group" and "The Grill Guru Owner Group". While the groups mainly started with sharing dishes, today you can find more and more enthusiasts posting about outdoor cooking. Many examples can be found of homebuilt outdoor cooking areas ranging from a more compact setup to a full scale barbecue area (see figure 13). It also seems that companies are jumping in, with neat outdoor kitchens with a kamado at the centre (see figure 12 and figure 14).

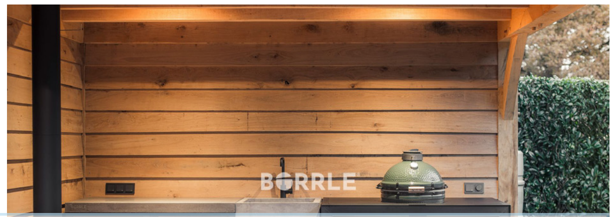


Figure 12. Left: Promotional picture from company Industrialz (Industrialz, 2021)
Figure 13. Right above: home barbecue area, posted on the Facebook Bastard group
Figure 14. Right below: Promotional picture from company Borrle (Borrle, 2021)

Conclusion

Where many people tend to be very proud of their barbecues, the same users tend to be quite insecure about their cooking skills. This is something to keep in mind; making sure the product is simple, helps the user but also empowers the user in their barbecue. There are many people that have a kamado to show it off to people, so the designed product should be something that the user can be just as proud of.

/PERSONAS

Ben, 31

Experimenting
Confidence
Cooking experience
Likes gadgets
Looking for status
Spending power €€€

Ben loves gadgets. He has a girlfriend and no kids, so he has quite a lot to spend. When he wants something new, he gets all information available out of enthusiasm, which was the case with his kamado. In cooking, he likes to show off his skills and gadgets to his friends. Furthermore, he cares about the environment which sometimes makes him feel bad about his barbecue habits.

"Whenever there is something new on the market, I'd like to be the first one to use it."

The Bastard | Once every 3 weeks | Beer

Main goal:
Impress people around him with his products.

Frustrations:
- Keeping the kamado at a certain temperature proves to be hard.
- If there would be sustainable solutions for a barbecue, he would be interested as long as they do not degrade his barbecue experience.

Hendrik, 45

Experimenting
Confidence
Cooking experience
Likes gadgets
Looking for status
Spending power €€€

For Hendrik, **cooking on his kamado is a good outlet** after a long weekday of his office job. He loves to be the pit master and to be the center of the gathering. For him its similar to being behind the wheel of an impressive car; **he likes to have control and to be in this alpha position** (although he would never say this out loud).

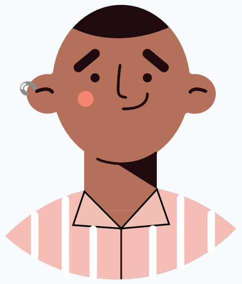
"I love to cook something exceptional for my friends, without being a real chef."

The Bastard | Once every 5 weeks | Craftbeer

Main goal:
To regain a feeling of manliness and a certain prestige.

Frustrations:
- Keeping the kamado at a certain temperature proves to be hard.
- Sometimes he is not able to speak to visitors as much as he would like.

Jamie, 38



Experimenting
Confidence
Cooking experience
Likes gadgets
Looking for status
Spending power €€€

Jamie has bought the kamado to add to his already complete cooking tool collection. He is working in a kitchen, and at home he likes to make his work into a hobby. He loves to experiment with different dishes, and to cook for bigger groups of friends occasionally. **For him it is not about getting the biggest chunk of meat, but to get the best dish on the table.**

"I like to put as much effort in a meat replacement dish as people put effort in their steak."

The Bastard | Once every week | Wine

Main goal:
To please his guests as much as possible, while maximizing the possibilities of cooking on a kamado.

Frustrations:
- Keeping the food warm when having many people over.
- During a BBQ that continues into the dark, enough light can be a problem.

Figure 15. Three proposed personas; types of clients of 200 Fahrenheit.

To understand more about the user, three different personas are presented. These personas are based on four qualitative interviews, are verified by the head of the main store of 200 Fahrenheit and are compared with the persona that the company has made for the buyer of the brand The Bastard. Lastly, it is in line with Nationaal BBQ Onderzoek (Hielkema & boomsma, 2020). In Appendix E, a summary of the interviews can be found.

Persona Of The Company

The persona shown in figure 16 was made by the marketing department of 200 Fahrenheit, representing the buyer of The Bastard. This persona called Sander seems to be close to the proposed persona Hendrik, but there are some important differences. Although Hendrik might be close to Sander, the idea that Hendrik likes to be in the alpha position might be an underlying motive that is true for Sander as well, which is not yet noticed by the company. Also, the general buyer of the Bastard might think worse and less confident about his cooking than the persona Sander suggests. Lastly, the notion of Sander of having too much choice from different brands really depends on where he buys the kamado. This might be true if you look online, but if you come into a store, it should be pretty clear for a salesmen which barbecue fits your needs since their target group is quite defined, as found in the interviews with multiple vendors.

Figure 16. Persona of The Bastard, made by the marketing department of 200 Fahrenheit

Conclusions Personas

If we look at the three created personas, 200 Fahrenheit mostly focusses on Ben and Hendrik. The third persona Jamie represents a more professional group, a real food and kitchen enthusiast that is looking for more professional tools to serve his big group of friends that come over for dinner. We found that kamado barbecue cooking is becoming more professional, so this is a market that 200 Fahrenheit should consider giving more attention. Also, this persona wants to maximize the possibilities of the kamado, which makes it interesting to design an innovative product for him. Fortunately, designing for this persona does not necessarily exclude the other two personas. The product will be designed to be professional and useful in the first place, but this could manifest as a status product as well which is important to the persona Hendrik. Furthermore, the product could be attractive for a gadget lover Ben.

Analysing The Buying Process

To verify if these personas also applied to the people that salesmen experience, two interviews were conducted. One with the main salesman of the store "Harlem BBQ", which is the physical store owned by 200 Fahrenheit. The second interview was conducted with the barbecue expert of the store Intratuin in Cruquius. A summary of the interviews can be found in Appendix E.

Important Takeaways

We can conclude that there is a fascinating paradox happening. Generally men that buy products that are marketed for though guys with tattoos, while they commonly are just regular people. And as the salesmen stress; their partner is usually in charge of the money, while his or her needs are sometimes ignored completely in products. The salesmen stated that he noticed that women paid attention to different details, like if the barbecue tong would fit in a dishwasher. The goal should be to design a product that is both masculine enough for the man to want, as practical enough for the woman to approve. And at the same time, it may not harm the barbecue experience in any way.

Something that was noticed by the vendors that usually when people buy their first kamado they often come back for more products, with as an important motive that they want to cook for more people; "As soon as I told my friends I have a kamado, everybody started to invite themselves over!".

/HOW A KAMADO WORKS

What makes a kamado so special?
The main properties that set the kamado apart from a common kettle barbecue is its ability to retain heat and its ability to control the in- and outflow of air, which results in a barbecue of which the temperature can be regulated precisely. In the following chapter the different kamado parts and their functionalities will be highlighted. It will focus on the parts that common large kamados have, although this might differ slightly between some brands because of different designs or cost reductions.

The Parts Of A Kamado

The outer shell of a kamado consists of two main parts; the dome and the base with the dome containing the air outlet often referred to as the topcap, and the base containing the air inlet often referred to as the damper. Both the topcap and the damper regulate the amount of air moving in and out of the system. An air tightening gasket located in between the dome and the base closes the system. The dome and the base are usually clamped between metal bands which are connected to a spring loaded hinge system, which makes lifting the dome easier and damps the movement during closing. Since both the base as the dome are made of a thick insulating ceramic, the kamado is significantly better in retaining the heat compared to a thin metal shell kettle barbecue. See figure 17 for an overview.

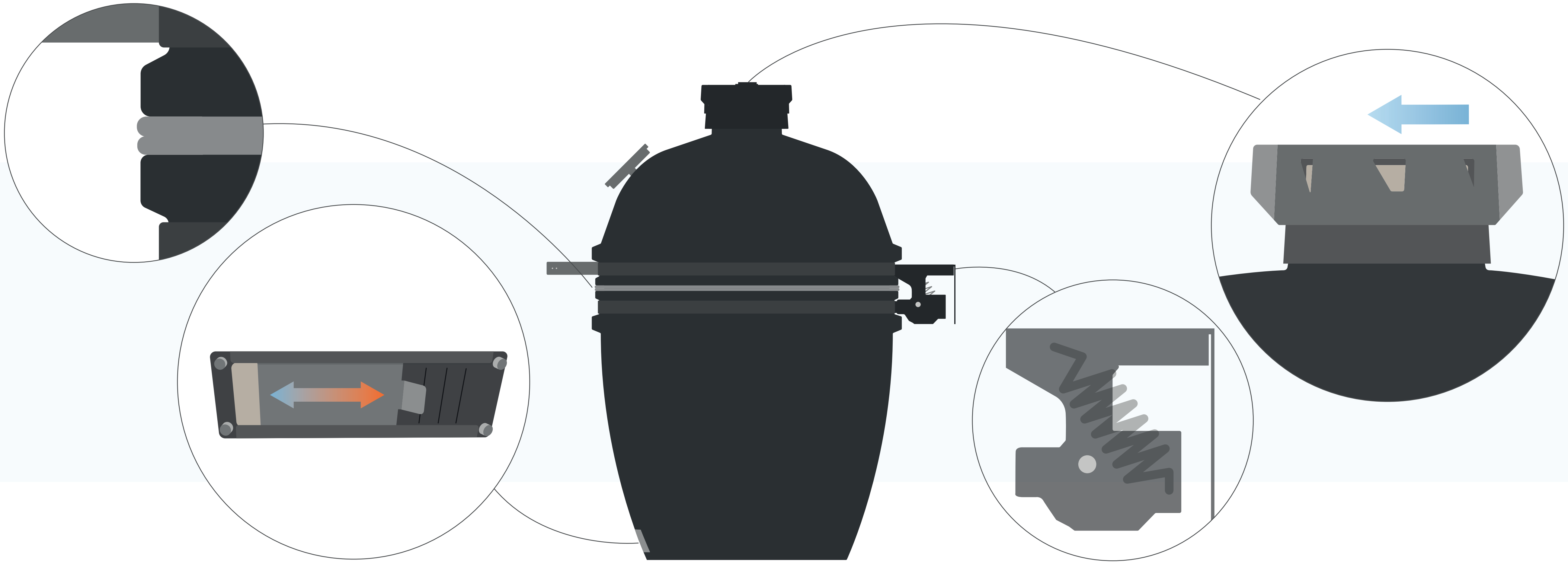


Figure 17. Overview of the key outside parts of a kamado

In the base, a ceramic firebox is located which adds protection to the base and further lowers the heat loss to the outer shell. At the bottom of the firebox usually there is a bucket to catch ash. Above the ash bucket there is a charcoal basket which holds the fuel of the kamado. When the kamado is lit, air is pulled through the damper, through a hole in the firebox, through gaps in the charcoal basket into the fire.

Above the firebox, a ceramic fire ring is placed. On top lies the metal plate setter, which holds both the grill and the optional heat deflectors. The heat deflectors give the opportunity to either cook with direct or indirect fire. Since the difference between these processes is crucial for the function of a kamado, it will be further explained further in this chapter, under heat transfer basics. This complete setup enables the heat to move upwards from the fire, circulate in the dome until it exits via the topcap. See figure 18 for an overview of all parts.

Around the kamado different products or add-ons can be found, of which side tables and a chassis with wheels are common.

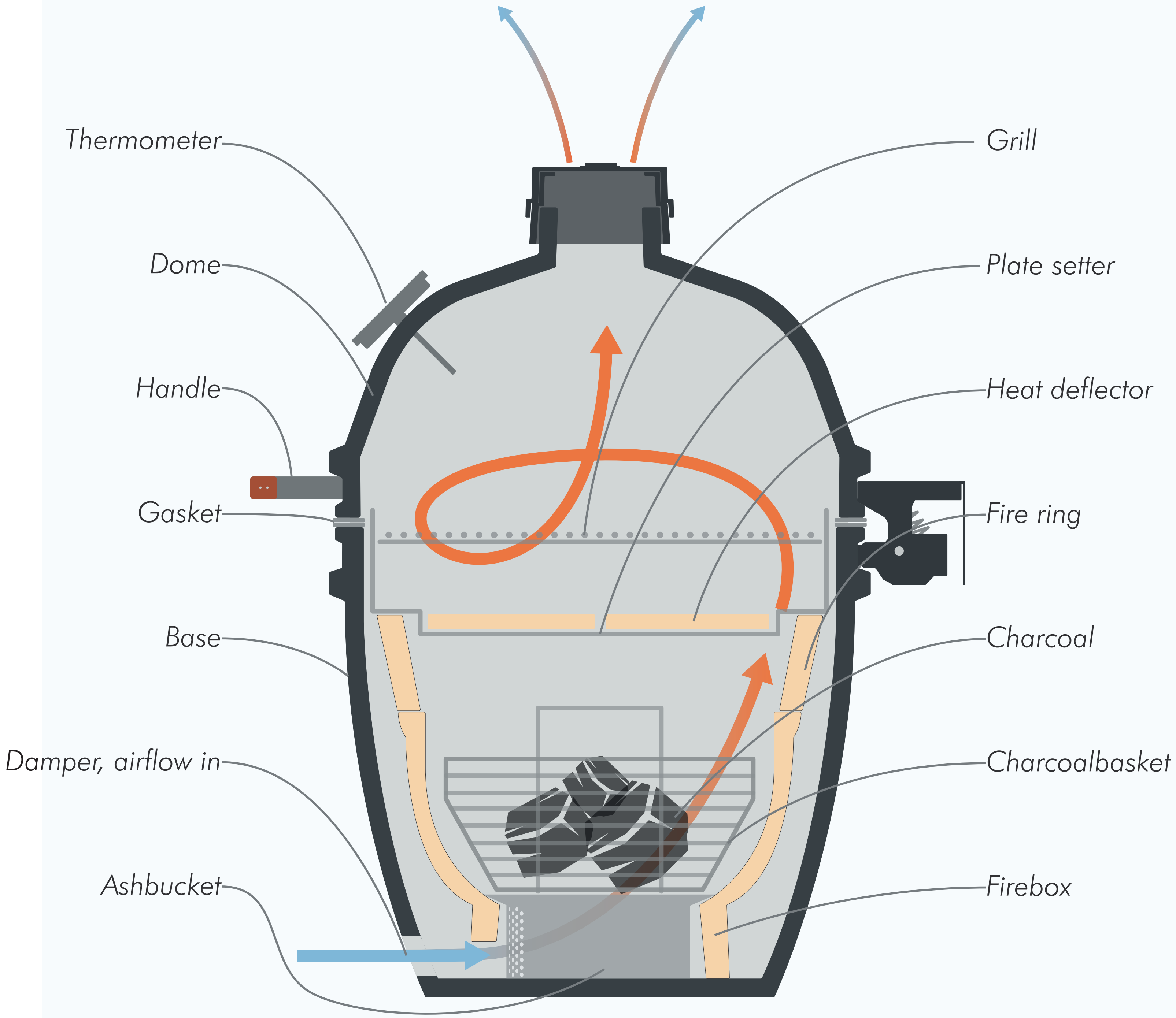


Figure 18. All parts of a kamado barbecue including their names

Heat Transfer Basics

Cooking on a kamado relies on three crucial heat transfer processes; conduction, convection and radiation. If the user is able to understand and control these processes, the kamado can be a great versatile cooking instrument.

Radiation means heat dissipation from the burning coals in the form of electromagnetic energy. "… is emitted by a heated surface in all directions and travels directly to its point of absorption at the speed of light; thermal radiation does not require an intervening medium to carry it." (Encyclopaedia Brittanica, 1998) The following principles are crucial for the process within the kamado:
- The higher the temperature in the air between the source and the product, the more effective the radiation.
- The efficiency of the radiation decreases when the distance increases. Two times the distance results in four times less radiated heat transfer, to the distance between the fuel and the grill is crucial. (Jeroen Hazebroek, 2020)

Conduction is heat transfer that takes place between two mediums that are in direct contact. When black stripes appear on your dish, this is because of the heat conduction from the metal grill. Metal has a high heat conductivity, so its captured heat will quickly move from the grill to the grilled substance. At the same time, the grill has a big surface area so it will absorb heat through radiation and convection quickly from the heat source.

Convection is the heat transfer that takes place when a fluid or gas is heated and carries the heat to in this case the food. (KBQ, sd) Since the kamado is closed most of the time, the heated gasses do not escape the dome directly but first tend to circulate around the food. This captures fluids that evaporate from the food, which keeps the food more moist compared to open barbecues. This circulation also causes the food to be cooked from all sides, which means the food has to be turned less frequently compared to a normal grill. Lastly, it is a useful process in for instance smoking, since the food will have a long time to absorb flavours from the smoke before it exits the kamado.

Cooking On A Kamado

A kamado is a versatile cooking instrument, being able to maintain low temperatures for hours as well as flying to over 350 degrees Celsius within a short time. As mentioned before, there are two main ways of arranging a kamado: suitable for direct and for indirect cooking. **Direct cooking** means that the dish has eye contact with the fire. This is perfect for grilling and searing; creating the dark stripes on your food. Generally, this is done at the end of the cooking process, to make a dish crispy on the sides after it is almost fully cooked. On the other hand, there is **indirect cooking**. In this case the eye contact with the fire is blocked by heat deflectors, causing the food to cook mainly by convection. Generally this is done at lower temperatures, to cook the dish slower and evenly. Since the airflow can be controlled so exact on a kamado, low temperatures of for instance 100 degrees Celsius can be easily maintained for hours. Because of the heat retainment capabilities of the kamado and the continuous "pinched off" airflow during indirect cooking, the charcoal will burn up relatively slow, being able to burn for hours without a refill.

Low and slow is a way of slowly cook with indirect heat. A classic dish to prepare with this method is the brisket. The brisket is a piece of meat from the chest section of a cow. Because it supports a lot of the weight of a cow, it consists mainly of connective tissue and muscle fibres, which need to be cooked using low heat for a long time to break down into tender results (Goldman, 2017). Properly cooking a brisket can take over 10 to 20 hours, depending on its size. 25% of this piece of meat usually consists of collagen. If you would cook this fast, it would snap up like rubber bands which makes it tough. If it is cooked slow however, hydrolysis takes place which breaks the collagen down to gelatine which makes it tender. Another important process is the rendering of fat. The fats in a brisket are mostly saturated, which need a high temperature to break down. If they are cooked long on a low temperature however, they break down and liquify which is called rendering. This makes the meat juicy and tasty. (Hanson, 2014)

Smoking is a cooking method that is usually done in combination with low and slow, is smoking food. This can either be done cold with wood shreds slowly burning, or during low and slow cooking with bigger chunks of wood put on top of the simmering charcoal. There are multiple types of wood that can be used, with all their own kind of flavour. As the wood burns, the smoke circulates around the food to eventually penetrate it with its flavour. When smoking meat, a red ring on the sides of the meat can be seen when it is cut, which is the result of the chemical reaction of the smoke that has bonded with the meat.

Planning your dishes; one downside of a kamado is that once it is hot, it retains its heat so well that it is hard to get the temperature down again. This means that if you choose the order of your dishes you should choose wisely, because going from a seared steak at 350 degrees Celsius back to a slowly cooked salmon at a maximum of 100 degrees Celsius is simply not possible. If one thinks to open up the kamado to let out the heat, this will only add more oxygen to the fire which causes the temperature to rise even further. A good sequence in dishes would be to start with smoking a salmon, then a period low and slow with a piece of meat, searing off this piece of meat at a higher temperature, and ending the evening with a pizza, which needs about the highest temperature you can achieve.

/CAPTURING RESIDUAL ENERGY

There are multiple ways of capturing energy from the kamado, of which two basic principles are most feasible. The first if to capture it in the form of heat, in a medium like water. The second is to convert heat to electrical energy using a Peltier element, also known as a Thermal Electric Generator. In this chapter, the possibilities of this technology will be researched and secondly, the current energy system of the kamado will be analysed.

Peltier Elements

Next to capturing heat, a Peltier element can be used to convert heat to electricity using a phenomenon called the Seebeck effect. Peltier elements are also known as Thermal Electric Generators or Thermal Electric Coolers, depending on the application. It can either create a thermal difference between two plates if electrical power is applied to it. It also works the other way around; it creates electrical power when a thermal difference is established. The electrical output relies on multiple factors, but generally the bigger the temperature difference, the higher the power output. With a temperature difference of 150 degrees Celsius, 5 watts are not uncommon to be reached per element. On a kamado, this significant temperature difference is available with burning coals inside and a relatively cool environment.
As an expert from the company TE Technology states; “The power conversion efficiency is dependent on a variety of factors, although typically it might end up at around 3%” (P. Lau, personal communication, April 26, 2021). Although it might be possible to optimize this efficiency to the desired application, we will take this efficiency for further calculations.

Peltier elements are commonly used to power small applications on pipelines and to recover energy from exhaust gasses. Furthermore, they are implemented in wearable devices to generate small amounts of electricity from heat of a human person (Nesrine Jaz iri, 2019). An interesting implementation of the technology is the Biolite CampStove 2 (bioliteenergy, 2017). It is used to cook in the wild, creating a fire from only wood sticks, twigs or pellets. While it cooks, it conducts heat to a Peltier element which is in this case a Thermal Electric Generator (TEG), generating a maximum of 3 watts of useable power to charge electrical devices. At figure 19, a snapshot from an explanatory video from their website is shown. From the power it generates, also a small fan is powered which cools the cool side of the TEG. This is needed to create a constant temperature difference, which is crucial for the power output of the TEG. After the cooling air passes the heat sink placed on the cool side of the TEG, it is guided into the fire causing it to light up more and to decrease the generation of smoke.
Despite its low power conversion efficiency, using a Thermal Electric Generator to generate electrical energy from residual heat energy makes a great range of “cordless” product ideas possible.

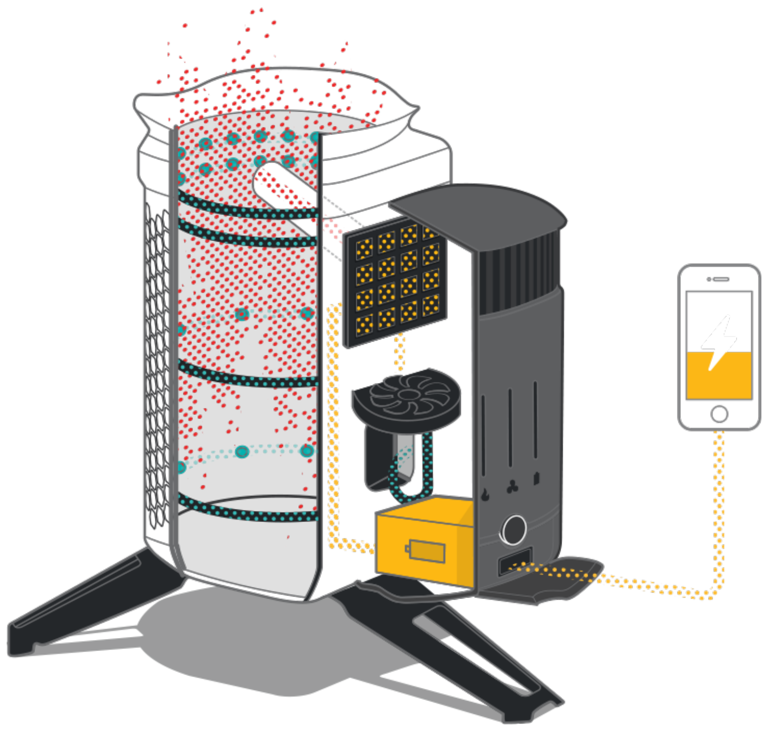


Figure 19. Snapshot from an explanatory video of the Biolite CampStove 2, explaining the working principle. (bioliteenergy, 2017)

Determining The Order Of Magnitude Of Available Energy

To get a glimpse of what could be possible with the rest energy from a kamado, an initial rough estima-tion of the total energy system can be done. We will take the Bastard Large as a benchmark, since this is a common size on the market and has been sold significantly more compared to other sizes (around 65% more than The Bastard Medium (200 Fahrenheit, 2020)). As mentioned earlier, heat is retained in the kamado because of its highly insulating ceramic shell. The airflow is precisely regulated at the opening and the bottom with neglectable air leakage, thus barely unnecessary heat loss.
Generally, about 3 kilograms of charcoal fits in a large kamado. In most situations it makes sense to fill the kamado to its full capacity, since as soon the air vents are closed after usage, the fire dies out and the leftover charcoal can be used again later. One kilogram of charcoal contains about 30 Megajoules of energy , which we assume is virtually all converted to heat in the burning process (GIZ HERA, 2011).

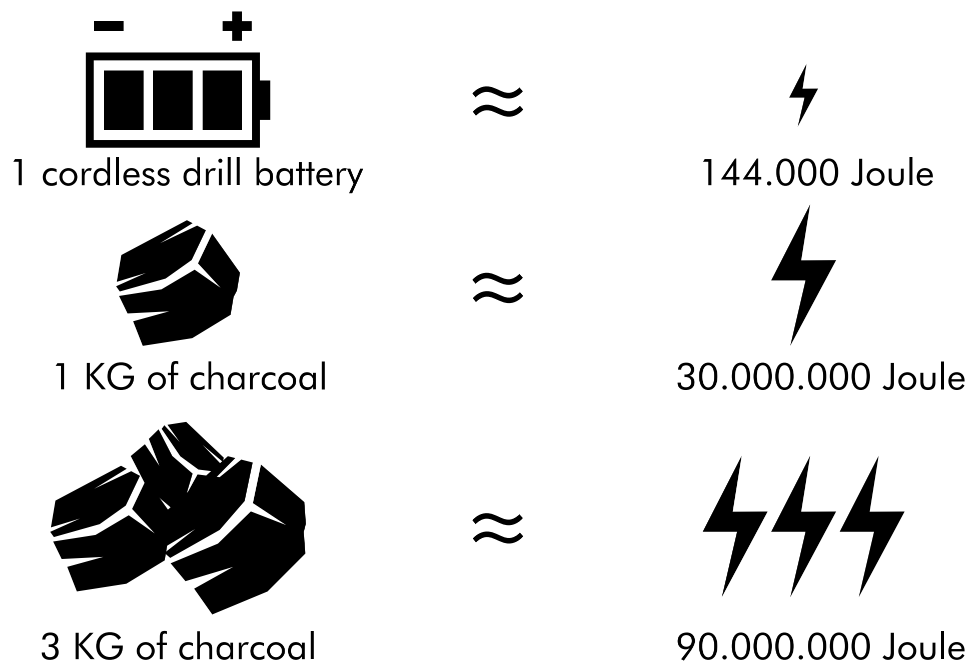


Figure 20. The total potential energy of charcoal, compared to that of a common cordless drill battery for scale.

Rough Estimation Of Capturing Heat Via Air Versus Via The Ceramic Shell

So we have a total of 90 Mega Joule. First, a conversion to heat energy of approximately 100% is as-sumed. Then we assume that approximately 30% of the energy is lost via the ceramic outer shell, and 70% via heated air that exits the topcap. Although burning time differs significantly over the airflow settings of the kamado, we take an average burning time of 4 hours before the charcoal is burned up completely. When this is calculated, it gives an average heat energy power of 1875 watts via the ceramic, and 4375 watts via the air during the burning time of the charcoal.
We assume that only the dome (upper shell) warms up significantly, because of the warm air moving upwards and because of the firebox blocking the heat to the sides at the bottom of the kamado. If we then calculate the needed area covered with TEGs to generate either 50 watts (enough to power a coolbox) or 5 watts (4 small computer fans/charge your phone), it gives respectively 88% coverage and 8.8% coverage of the dome.

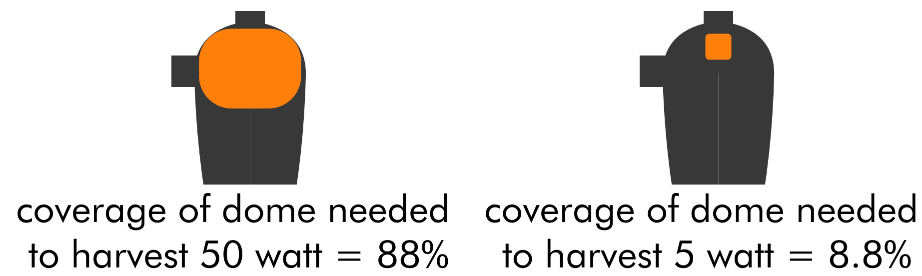


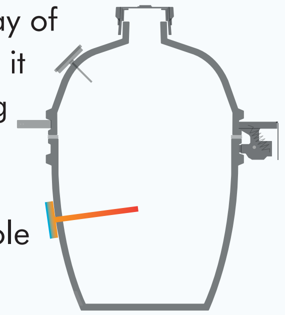
Figure 21. Putting experiment outcomes in perspective

Conclusion

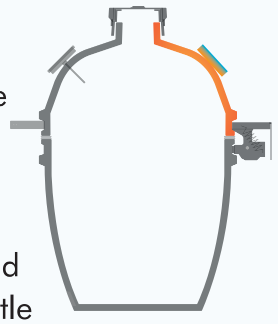
This calculation and the learnings from the Biolite CampStove 2 (bioliteenergy, 2017) are a good indica-tion that there is not enough energy available to power a cool box, but that powering a small electronic device should be possible. Furthermore, research should be done on where energy can be harvested, how much energy can be harvested there and how they compare in terms of practical application for a product. This will be analysed in chapter "heat output of a kamado".

Measuring The Capturable Heat Output Of A Kamado

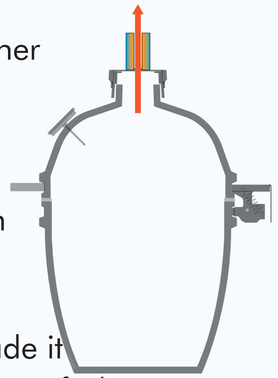
To determine the capturable heat output of a kamado, multiple experiments were conducted. Three ways of harvesting residual heat were analysed, determining heat energy in wattage. The three principles of capturing heat were; capturing heat via the outgoing air, capturing heat from the ceramic dome and capturing heat by sticking a highly conductive beam into the base of the kamado. The gathered results have been compared, discussed and verified by triangulation and reviews by experts. A thorough description of the experiment can be found in Appendix C.



Power through heat conducting beam (25-32 watts) could be a way of harvesting energy, but performed significantly worse than air. Secondly, it is questionably if it is really harvesting residual heat, or if it is just taking away heat that would otherwise have been used for cooking. Lastly, it could be a design limitation that it easily fits through the hole of the brand Grizzly, but if it would be used for Bastard or GrillGuru a new hole needs to be created.



Power through ceramic (14 watts per 16cm2) gave little energy, but on a small surface. This means that if the surface would be larger, more energy could be caught. In this way, it could be competitive with the power harvested from the air experiment. A downside of this method is that it needs some kind of heat conductive paste on the dome to make the heat conduct well to the receiving medium. A second downside could be that the first half hour the ceramic has not heated up yet, so no or little power can be harvested during that moment.



Power through air (131 watts) provided by far the most energy. Another upside is that it only requires a redesign of the topcap, which is a part that is relatively easy to replace. A downside is that by implementing this solution, the system might become a high obtrusive tower on top of your kamado, while a flat solution placed on the ceramic might result in a more visually attractive design.
Because the measured power was significantly more than the other experiments it seemed attractive to continue with this method, which made it crucial that this number was right. That is why triangulation was used to verify, by measuring the airflow and the temperature of the air. This gave a rough range of 104 to 149 watts, which increases the reliability of this number significantly. The data of the second experiment can be found in Appendix B.

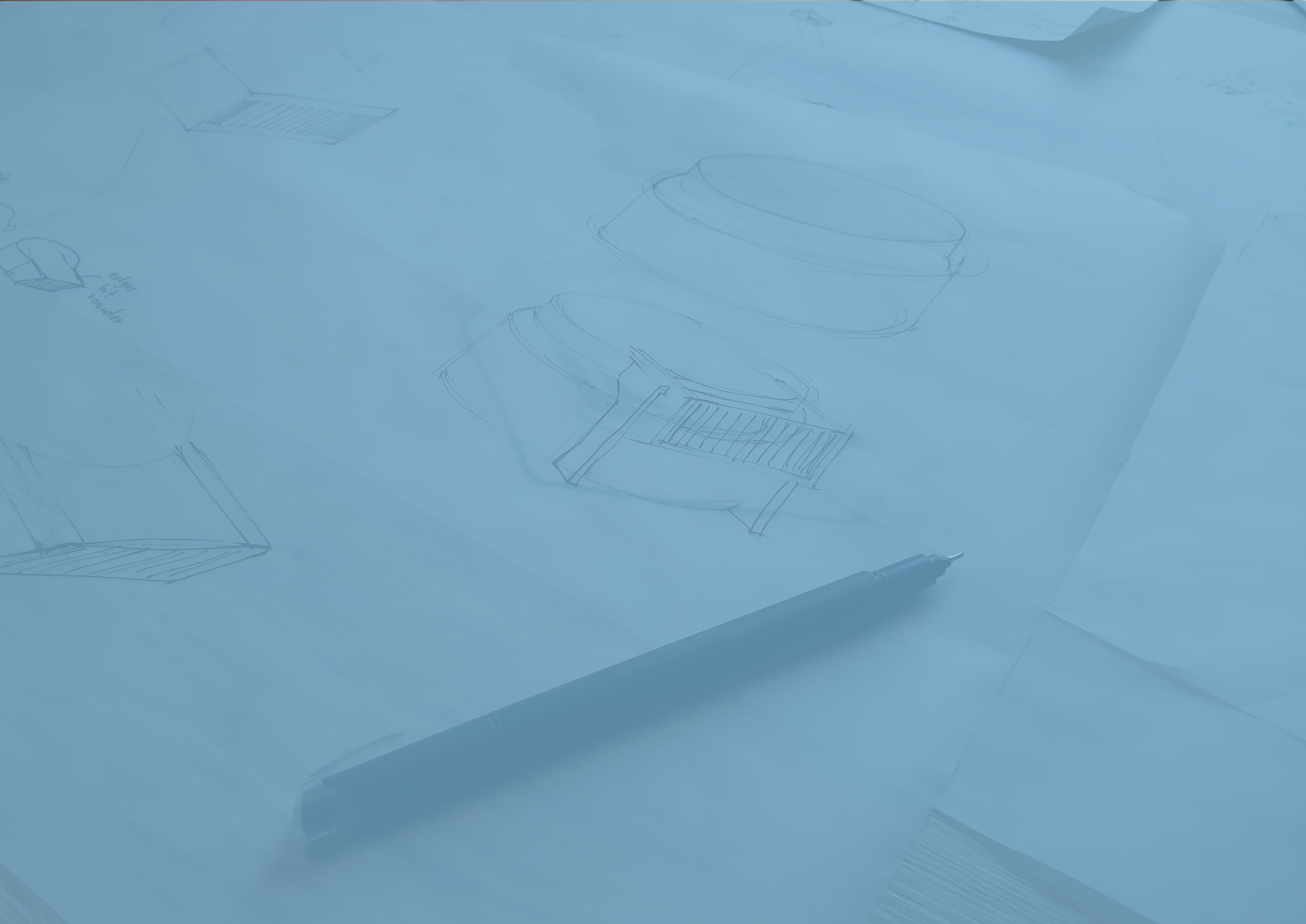
Harvesting electrical energy
As mentioned before, according to the advice of the consulted expert of TE Technology approximately 3% of heat energy can be converted to electrical energy in practice. Using air to power the system would mean a possible electrical energy power source of almost 4 watts. This is lower than the estimation done before the experiments, but in the same order of magnitude and definitely fruitful to gather meaningful ideas in the next phase.

Impact On Further Design

Extracting heat from the exhaust has proven to be the most promising and effective method. Secondly, it is least obstructive to the existing design since it would require a redesign of the topcap instead of a hole in the base or a dome that is fully covered by Peltier elements. In the ideation phase all three ways of capturing heat will be considered knowing the limitations, because an extraction method could suit a certain idea method better.

Conceptualisation

From the research and analysis phase, we dive into the conceptualisation phase. This part has consciously been chosen to be relatively short, since validating the feasibility of implementing new technology was crucial to the company. As stated before, for the company most innovations are interesting and valuable since on the market generally little innovation takes place, which means that any innovation would be of great value to them. Since a new technology is implemented, failure of the technology would present a bigger risk than failure of the concept.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/IMPORTANT TAKEAWAYS RESEARCH & ANALYSIS

Starting the conceptualisation phase, the research phase is wrapped up in a summary containing the most important takeaways to keep in mind when creating ideas. Most of these takeaways can also be found back later in the program of requirements. Next to these takeaways, the personas are kept in mind to create desirable and valuable ideas.

1. The product should work, powered by residual heat of an ignited kamado, which is at least 100 degrees Celsius.
    a. *The product is allowed to use a maximum of 4 watts of electrical energy*
    b. *The product is allowed to use a maximum of 150 watts of energy in the form of heat.*
2. The product makes the barbecue experience easier for the user.
3. The product gives the user confidence in cooking.
4. Fits into daily life for the partner instead of being only a cool gadget
    a. *The product is dishwasher proof*
    b. *The products appearance can be slightly softer and friendlier. The product must stay close to the identity of the brand however.*
5. The product should appeal to today's trends as described in the Research & Analysis phase.
6. The product should appeal to the proposed persona, described in the Research & Analysis.
7. The product should not interfere with the BBQ experience "fire, excitement and danger". One way to achieve this, is by making it not too technical or hard to operate.
8. The product should enhance the "Alpha position feeling" of the barbecue operator.
9. The product should be a guide towards a more sustainable line of products at the company.
10. The power source of the product should not be as low, such that replacing it by a simple battery would be an equally workable solution.
11. The product does not use an external source of energy besides the recaptured energy.

/IDEATION

To be able to obtain a large number of ideas, different methods were used. Firstly, qualitative research was conducted and combined with ideas that came up along the way. To make them futureproof and fitting to the context, these ideas were verified with the earlier culture and trend analysis. Also the How-To brainstorm method described in the Delft Design Guide (Annemiek van Boeijen, 2013) was used, based on the frustrations and possibilities encountered. Multiple brainstorm sessions were conducted, alone as well as with a fellow student that is an expert on thinking in new solutions. Afterwards, three promising ideas were presented to the company and together we picked the most promising one to work out in the verification phase, as validating was deemed most critical.

Selection And Development

Firstly, a selection was done based on the technical feasibility and viability of the gathered ideas. The ideas that remained were worked out further, to cover all possible applications and variations. An overview of the most essential take-aways from the research phase was made, which can be summarized in "culture", "trends" and "frustrations".

Figure 22. Visual representation of the idea selection approach

Key findings

Culture

BBQ =
Fire
Excitement
Danger

Cooking on a kamado can be a mental outlet

Drinks are usually seen as an important factor during a barbecue

Usually, a man controlls the grill rather than a woman

The grill operator has a certain "alpha" position

55% of electric grills are operated by woman

A Bastard buyer generally spends more money

The "Bastard buyer" is a very broad group of people.

Trends

"Dutch BBQ" is losing popularity

People are putting more time and effort in dishes

Meat replacers

Outdoor kitchen, outdoor cooking

Sustainable cooking, sustainability

Many US trends come to Europe

People are insecure about their barbecue competences

Kamado cooking is becoming more professional

Woman are becoming more important in the buying process; make products woman friendly

Frustrations

Cooking for a big group is often hard

Moving to the kitchen again and again is annoying

Planning the dishes is hard

Barbecueing in the dark can be hard

Cooking meat right is hard

Keeping the barbecue at the right temperature

At night, it quickly becomes too cold to sit outside

Matrix Of Relevant Findings Versus Top Three Product Ideas

When creating a matrix where the relevant findings mix and match with the three most promising ideas, a convincing picture becomes clear for the idea of an au bain marie container. The trends that match with this idea also match well with the defined persona which make it even more promising

Key findings	Bain Marie Container	PID Controller	LED	All Concepts
	Cooking for a big group is hard	Cooking meat right	Barbecueing in the dark	Sustainability
	Moving to the kitchen again and again	Keeping the BBQ at the right temperature		Woman friendly
	Outside cooking	Trends from America		People are insecure about their barbecue competence
	Outside kitchen			
	More time and effort in diches			
	Kamado cooking becomes more professional			

Figure 23. Matrix of key findings and top three potential ideas

/THREE POSSIBLE DIRECTIONS

Light

A small LED can be powered by a Peltier element, which is driven by residual heat of the kamado. The LED can function in multiple ways. Firstly, the LED can be pointed at the centre of the grill, making a late night barbecue a lot easier, and solving one of the frustrations that was found during the user research. Furthermore, the LED could be equipped with a thermometer of which the temperature can be communicated by either projecting it on the kamado or on the ground. The light could communicate it by either projecting numbers, or by certain colours that indicate that the temperature is right or too high/ too low, depending on the settings. It could also give feedback on recipes, by for instance starting to draw attention with light signals as soon as a timer has expired.

Appeals to;

- People being insecure about their barbecue skills
- The struggle of barbecuing in the dark

PID Controller

A PID controller can regulate the temperature of the kamado. This product does this by measuring the temperature inside the kamado and changing the fan speed accordingly. The more air is pumped into the system, the higher the temperature will be. This kind of product already exists, however they commonly work on batteries or normal AC power. The challenge would be to let the product be powered by the residual heat of the kamado. This should be feasible, since we measured that the Flame boss 500 uses a maximum of 2.88 watts if the fan is blowing at full power, and we estimate that the Peltier elements will provide us with around 4 watts of electrical power. This product would be controlled by a phone application.

Appeals to;

- People being insecure about their barbecue skills

Bain Marie Container

A container next to the kamado, which is kept warm using the residual heat from the kamado. The water flows from and to the topcap, capturing residual heat. The water can be pumped around by a water pump that is powered by a Peltier element. The Peltier element would be heated by the air coming out of the kamado and cooled by water, thus creating the temperature difference which produces power.

This product has two main features. It keeps the food warm that the user has just made with many sweat and tears, instead of letting it cool down on a plate before it arrives at the table. It could also be used to heat up food, sauce or chocolate, although it will probably not heat up fast because of its relatively low heating capacity.

Appeals to;

- Professionalizing of the barbecue
- The low and slow barbecue culture
- Creating an outdoor kitchen

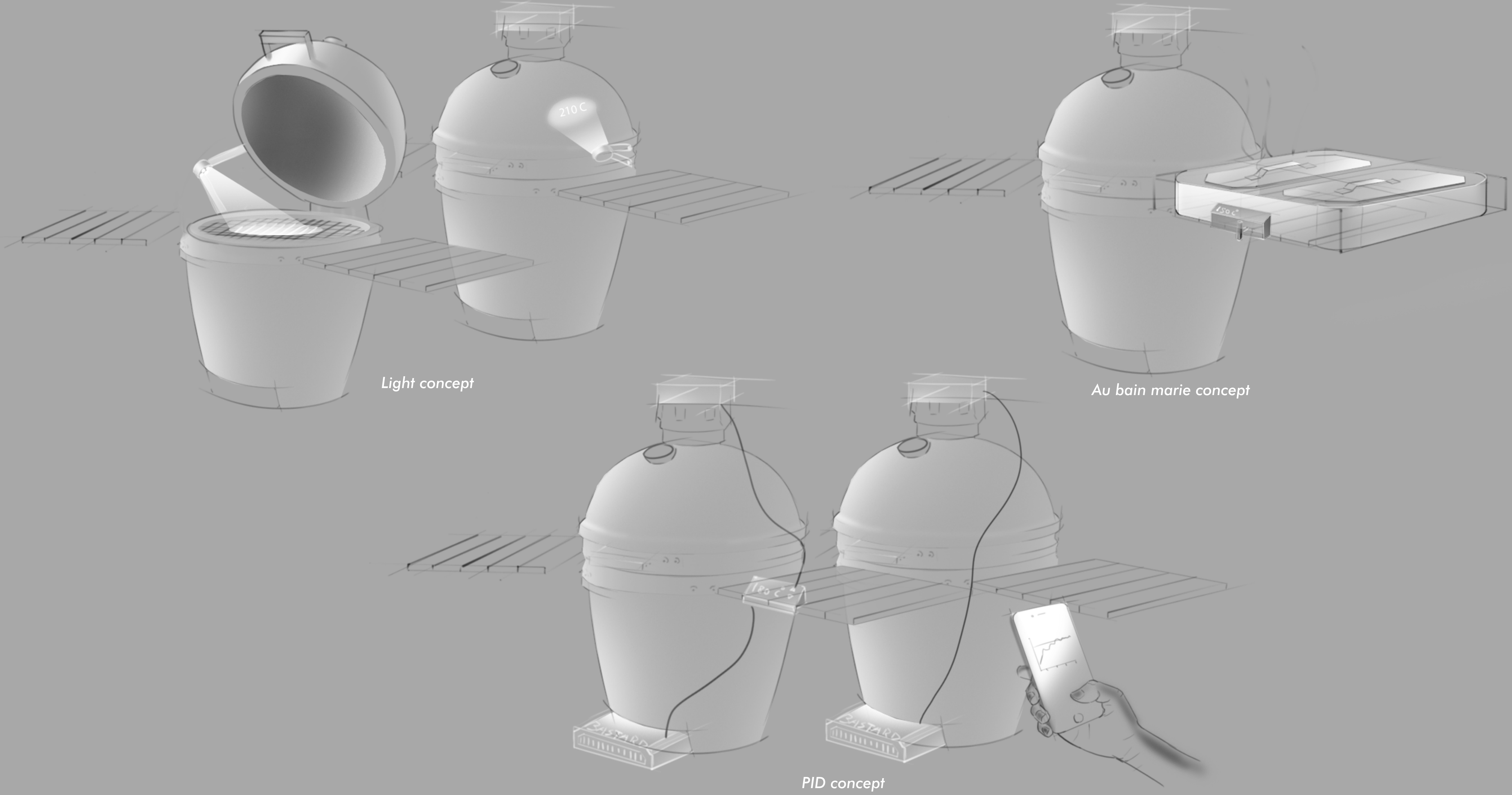


Figure 24. Concept drawings

/CHOOSING A DIRECTION

If we look back at the persona that was chosen, professional cooking and cooking for bigger groups were the users most crucial needs. When we lay that next to the three possible directions, the au bain marie is clearly the most desirable direction to pursue. This concept would be most elegant in terms of technical functionality as well. Where an LED could easily be replaced by a small battery, this concept could be able to replace a heat source of 130 watts which gives it significantly more impact.

After presenting it to the company, they liked the proposed ideas and agreed to the decision to pursue the au bain marie idea. Additionally, some conclusions were drawn together with the company during that meeting. Although I was already designing with mainly the Bastard brand in mind, we decided that this idea should definitely be for the Bastard user. The owner of a Bastard is the user that wants to let their meat rest in a suitable place, to obtain the best dish possible. Furthermore, setting and regulating the temperature is important, because this same user wants to do this perfectly. During this presentation, also a warming up sauce feature was presented. Although the product can probably still be used for it, it should not be designed specifically for that feature according to the company, because they thought this would not be a good unique selling point of the idea.
The company stressed that the most important outcome for them is to see if the implementation of this technology actually works. Tweaking the form giving or changing the producibility is something that can always be done by them later, but providing validation of the concept by working prototypes is crucial.

“The most important outcome for us is if implementing this new technology acually works.”
(200 Fahrenheit, 2021)

Embodiment

In the following phase, a concept is chosen to further work out to an embodied design. The next step is to analysed and define different details of the concept before a final program of requirements can be assembled.

The following questions arose when choosing this design direction, namely;

- What should the topcap, the au bain marie and the interface look like?
- How should the user interact with these three different parts?
- What electronics are needed to make the system functional?
- How big should the container be?
- How much heat loss should be taken into account?

By answering these fundamental questions, requirements for the product are defined working towards a program of requirements. From there, many iterations and validating experiments lead to the final design.

Figure 25. Testing the temperature setting functionality on a 3D printed topcap model

/DESIGN VISION

For me personally, the chosen concept is both challenging as intriguing in how it performs technically as a whole. The way it is self-sustaining in theory without having to add any energy from outside besides the energy that is already available is, I think, beautiful. For the company, this proposes a responsible way of thinking about energy which should rather be the norm than the exception. The designed product can be a step towards more sustainable design of their products. This way of designing is crucial, since sustainable and responsible design is becoming more and more relevant today. This can be directly seen in European developments, like the Sustainable Products Initiative which include new rules that have the potential to set the path for Europe’s transition to a less wasteful and more circular economy (European Environmental Bureau, 2021). The designed product should serve as a guide by showing how a product can be fully circular energy wise.

Visual Style

The collage shown in figure 26 shows a possible direction for the design, in formgiving and materialisation. The collage does not exceed the bastard style too much, which generally holds robustness, blunt shapes and dark colours. I want to take this style and give it a slightly softer touch, making it more accessible and giving it more credibility. In my opinion, The Bastard brand has already started to go in this direction by introducing the “urban” variant of their kamados. This kamado contains a grey non-reflective finish which is less hard on the eye and gives it a more professional and mature look. A few years after its introduction, the sales of this variant have exceeded that of the original, which indicates the relevance of this direction. The appearance of the thermometer has become more professional and mature, by using less colours and turning into a more minimalistic design.
However, as expert in rituals, product interaction and perception Dicky Brand says, the product should not swerve from the current design too much. The brand identity is robustness and bluntness which simply works greatly, by going too far away from this original style might lose the essence of the brand.

Requirement: the product should fit the visual style of the Bastard.

Requirement: The main colours of the product should be dark and mostly shades of black.

Requirement: The handles should be made out of dark brown bamboo.

Figure 26. Collage form and material

/AU BAIN MARIE

Working Principle

"Au bain marie" literally translates to "water bath" from French. It means that the prepared dish is put in a container, which is submerged into a container which contains water at a set temperature. The advantages of using water is that the dish will be kept at temperature gradually and evenly. Besides, water has a high heat capacity which means that the temperature of the dish can adapt to the set temperature quickly. The set temperature can be anywhere between 0 and 100 degrees Celsius. To keep a dish warm before serving is called a chafing dish, which is used often in restaurants between serving the food and preparing the food. Some chafing dishes are kept warm with candles, and some can be exactly set to a certain temperature using a knob and an electric heater. In most cases, the chafing dish is heated indirectly by heating water under it, which makes it a form of an au bain marie. In our case, we will heat the water using the outgoing heated air from the kamado. Since the United States' Food and Drug authority states that any hot foods should be served at a minimum of 60 degrees Celsius, we will take this temperature as a baseline for our product to reach (U.S. Food and Drug administration, 2018)

Interface To Set The Temperature

The interface to set the temperature should be minimal and fit the total feel of the brand. An example of an existing product where this has gone wrong is shown in figure XX, the Flame boss 500. This interface completely missed the essence of barbecue in this product. It makes a user feel more like a computer hacker than a grill master, with the blocky letters and the green, out of context, alienating screen colour.
Since our user wants to precisely prepare his or her dish, it is crucial to set the temperature of the au bain marie container. The interface does not need many options, since it only has to communicate the current temperature and the temperature it is set at. Although adding a screen might add more possibilities in terms of functionality, it might make it too complicated and expensive. Since the Bastard style is blunt, minimal an robust, a simple temperature indicator should suffice. In figure 29, a moodboard for the interface can be found. The actual interface will be worked out after all requirements are set.

Figure 27. A common candle powered chafing dish

Figure 28. The interface of the FLAME BOSS 500

Requirement: the product keeps food warm by heating water, as done in the au bain marie method.

Requirement: the product should be able to keep the water inside at a minimum of 60 degrees Celsius.

Wish: the user should be able to set a temperature between 20 and 90 degrees Celsius. The product should keep the water at the set temperature with an accuracy of maximum 5 degrees.

Wish: the product should be simple and intuitive to use.

Figure 29. Interface collage

Size Of The Au Bain Marie

Before further research about energy systems can be conducted, the size of the au bain marie must be determined. The size of the au Bain Marie was chosen to be 325 by 265 millimetres and 100 millimetres deep. The size was chosen based on two main requirements; it had to be small enough to fit on the table of a Bastard large, and it had to be big enough to facilitate the user with a place for (most) common dishes. This included four spareribs, one complete chicken or one brisket. A starting point were gastronome sizes, which are common in the catering industry.
To determine which size would be most suitable, an estimation of the sizes of the dishes where cut out of cardboard, as well as three suitable gastronome sizes for the container. The following sizes were taken; spareribs (300 to 375 mm long), one complete chicken (about 200x200x100) and the brisket (300mm long). The containers to try were chosen at 530 x 325 mm (1/1), 325 x 265 mm (½) and 325 x 176 (1/3) gastronome.
The 325 by 265 millimetre version turned out to fit best. It fit most of the dishes, and had a good fit on the table of the kamado. Although some spare ribs might be too long, these would be able to bend into the container most of the time. In the worst case, the user could fold over a too long spare rib, or cut it to make it fit.

User Test

For the height of the container, the main requirement was to give the user enough space to be able to make pulled pork or pulled chicken comfortably, without making the container unnecessary high. A user test gave that the standard of 100 millimetres would be a suitable balance. In figure 31, user Jelmer is making pulled chicken in a model of an au bain marie. To reflect the function of the container, boiling water was added to the pan below so the dish would actually be kept warm. After pulling, Jelmer took the pan inside to serve it to the guests since it started raining outside. There, the au bain marie served its purpose well throughout the dinner keeping the dish warm, which definitely improved the quality of the dinner.

Figure 30. quickly modelling average sizes of common dishes, comparing them to possible sizes of the container.

Figure 31. User testing a model of an au bain marie

Requirement: The product facilitates a space of 325 by 265 millimetres. The container will be 100 millimetres deep, conform common ½ gastronorm size. This is large enough to fit fits 5 commonly sized spareribs, one complete chicken or a commonly sized brisket.

Requirement: The product must fit on a side table of a Large Bastard and an XL Bastard (which have the same table size).

/DEFINING THE WORKING PRINCIPLE

As discussed with the company, the key feature of the product should be to keep the food warm that has been prepared, by using the residual heat of the kamado. As found in “Capturing Residual Energy”, the heat should be extracted from the air exiting the topcap, since here most heat energy is lost. This heat should be transported to the au bain marie container, which is located at the table of the kamado barbecue.

Energy System

The medium to transfer the heat is water, which is suitable because of its high heat capacity. Also, it is widely available and food safe. A water pump must be used to pump the water around from the heat source to the container. Electricity is needed to power the pump, which is why a Peltier element is added to the system. For a Peltier element to generate electricity, one side needs to be actively heated and one side to be actively cooled. The cool side of a Peltier element is usually cooled by either air using a fan (as in the Biolite CampStove 2 (bioliteenergy, 2017), see figure 32), or by pumping water passed it. Water cooling theoretically cools better because of its higher heat capacity, but it costs more energy to pump around. As long as there is a temperature difference between the two sides of the Peltier element, electricity will be generated. The bigger this temperature difference is, the more electricity is generated.
The water which transfers the heat from the topcap to the au bain marie can be used for both cooling the Peltier element, as for heating the container. This is because the water in the container will never reach 100 degrees Celsius and if it does, the water does not have to run anymore since the water in the container has reached its desired maximum temperature. The air that exits the kamado provides the heat for the hot side of the Peltier element. The kamados general lowest setting is 100 degrees Celsius. This means that there will virtually always be a temperature difference, thus electricity generated.

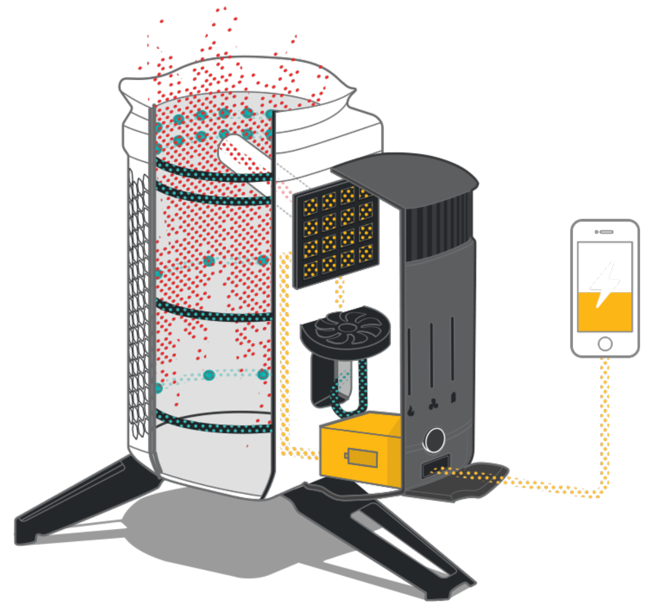


Figure 32. How heat and cold is guided to the Peltier element in the Biolite Campstove 2 (Biolite, 2021)

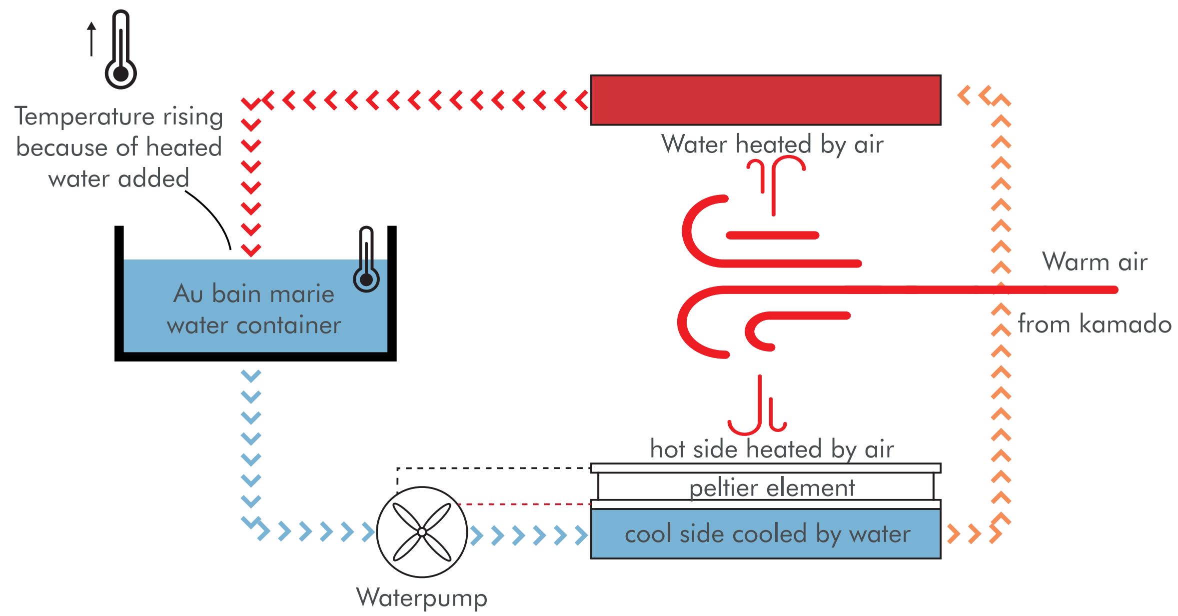


Figure 33. Initial envisioned energy circuit

%EFFICIENCY OF THE SYSTEM

The potential heat output of a kamado has been determined. From there, the efficiency of the system needs to be found, by doing a measurement on the heat loss. This will serve as a guide on how efficient the heat recapturing system, and how well insulated the au bain marie container need to be.

Localizing Heat Loss

Firstly, we need to determine where most heat is lost, and at which places it can be neglected. The biggest heat loss is located at the au bain marie container, since here the heat is spread over the biggest surface area in contact with cold outer area. We will take the water as the source of heat. The heat lost from the water can be split up into two main streams. One is via the sides and the bottom, through the double walled outside container of the au bain marie. The second one will be going up, through the food container and through the lid. The last location where heat is lost is through the two pipes that lead the water from the heat reclaim part to the container. However, this heat loss will be neglected because these tubes will be made of thick rubber, which has a significantly lower heat conductivity compared to the au bain marie. Also, the surface area of these pipes will be significantly lower than the container. A simplified overview of the system is shown in figure 34.

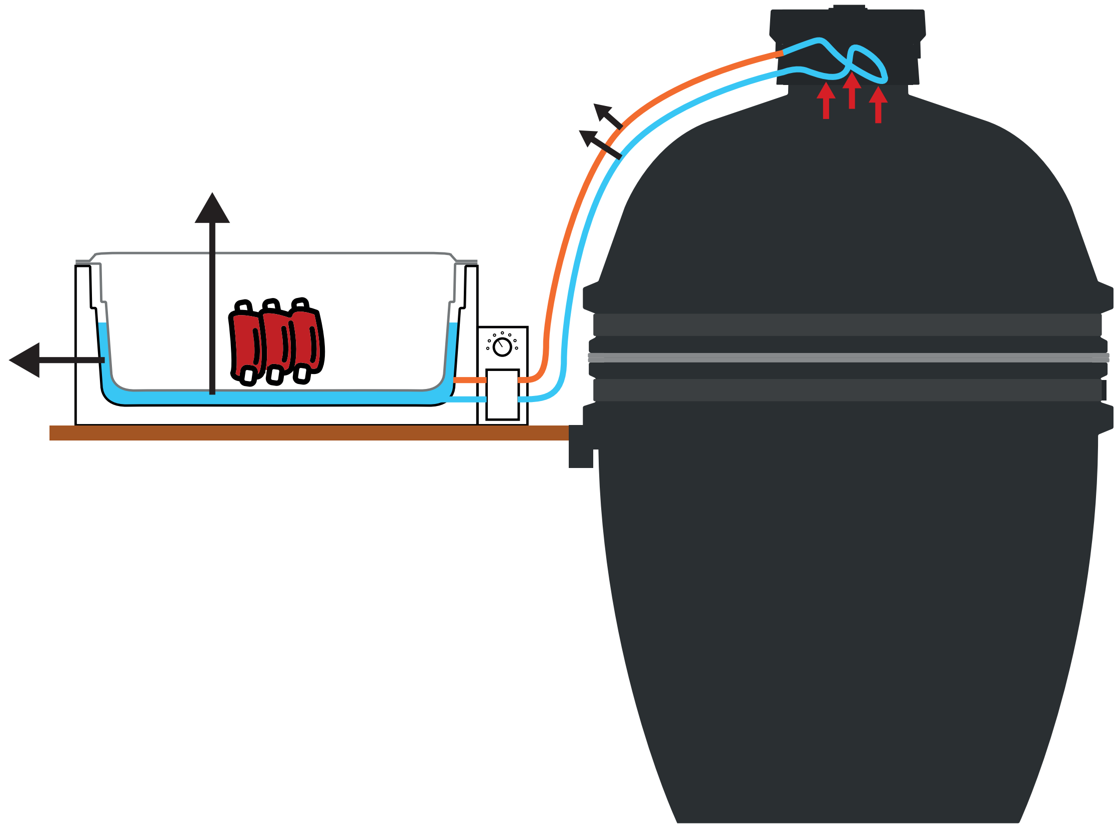


Figure 34. A graphic overview of the locations where heat loss will be taking place

Measuring The Heat Loss Of The System

Since there was no actual au bain marie available with the right size, a model of an au bain marie was made to test the heat loss of the system. In the test, a representation was made using three pans and aluminium tape to tape off any holes. Using an Omega digital thermometer with multiple probes the temperature of one litre of water could be monitored closely. The water was warmed up to around 60 degrees Celsius which is the minimum temperature it should reach. The data showed an average heat loss of 13.4 watts in a representative environment of around 20 degrees Celsius. With the total surface area of the outer walls of the test setup being 1583 cm2 and that of the proposed design 3790 cm2, the total heat loss will be estimated at 32.1 watts.

There should be enough energy to keep the au bain marie at a constant temperature of 60 degrees Celsius if the kamado is at a 100 degrees Celsius. This means that at least 32 watts of energy should be available from the kamado at a 100 degrees Celsius. If we estimate that a kamado at 250 degrees gives 131 watts of heating power is a 100% output (found in Capturing Residual Energy) and that at a 100 degrees Celsius the kamado gives 40% output accordingly, this gives that the kamado supplies 52.4 watts of heat energy at a 100 degrees Celsius. Although it should be stressed that these numbers are all rough estimates, it indicates that the system should be possible in the proposed configuration. If eventually too little energy is available, the solution could be to improve the insulating properties of the au bain marie, which can further increase its efficiency.

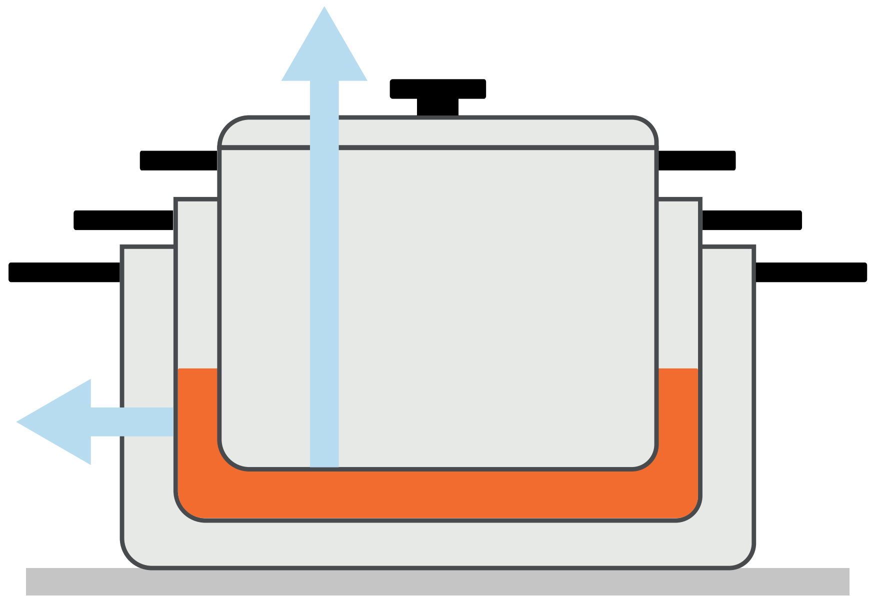


Figure 35. Visual of the heat loss test setup

Requirement: the product keeps the water at at least 60 degrees Celsius **when the kamado is at a constant temperature of 100 degrees Celsius.**

/ENERGY OUTPUT AT LOWER TEMPERATURES

We have found the potential heat output of the kamado at higher temperatures. However, there are many use cases where the kamado will stay at lower temperatures for a certain time. Here, the heat output is tested at the lowest occuring temperature.

During this experiment, heat fins were placed on the topcap and cold water was ran through the water block attached to the heat fins. The temperature at the grill reached 130 degrees Celsius, which is realistic for a low temperature dish. However, the temperature in the topcap stuck at 73 degrees Celsius and the temperature at the outlet of the topcap behind the heat fins was measured to only be 51 degrees Celsius (see figure 36). This meant both that the heat fins still captured a significant amount of heat because it drops 22 degrees Celsius passing the fins, but also that only relatively cool air actually reached the topcap. This is expected to be caused by two phenomenons. This is probably caused by the lower airflow that occur at lower temperatures. In the experiments described in "Capturing Residual Energy", a kamado temperature of 287 degrees was measured, a temperature of 267 inside the topcap and of 100 degrees Celsius in the air leaving the topcap. Furthermore, a high airflow was measured of about half a litre per second, while at low temperatures the airflow was too low to measure by the available anemometer, or to even feel by touch.
We expect that at low temperatures, the amount of heat lost via the ceramic is more significant compared to at higher temperatures. The higher airflow causes a lower resistance for the heat to be lost via the air. For a graphic overview, see figure 37. For the designed product, this means that the described phenomenon will cause significantly less heat energy can be extracted at lower temperatures. However, in this case still a temperature difference of 13 degrees Celsius was available, which means that the requirement of reaching a water temperature of 60 degrees Celsius can still be possible. During further development, the proposed product will be tested at both high as low temperatures to see if the requirement can be achieved.

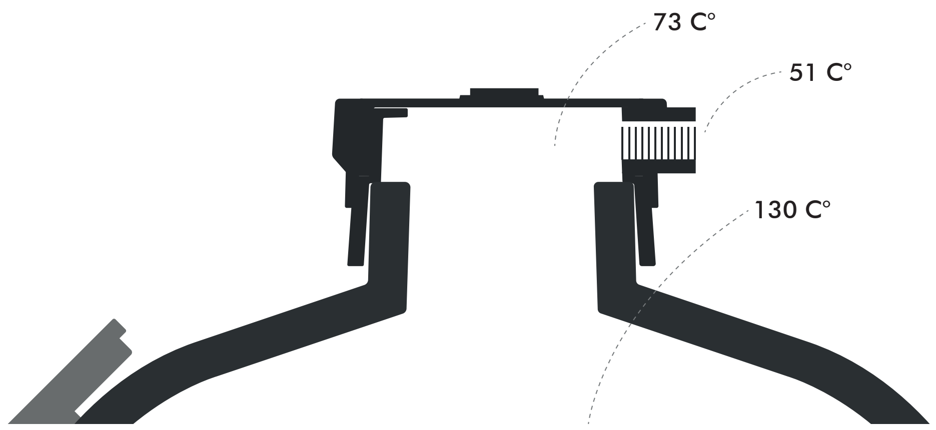


Figure 36. Measured data at low temperature experiment

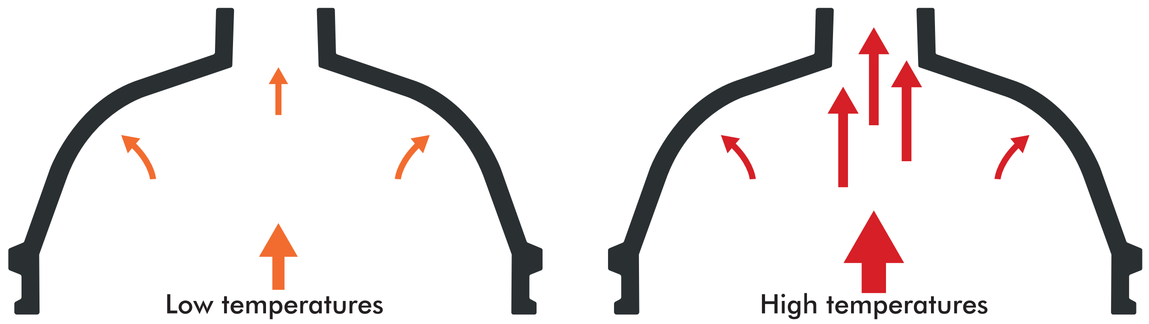


Figure 37. Graphic overview of energy flow at low versus high temperatures

/FINAL PROGRAM OF REQUIREMENTS

The program of requirements is based on the takeaways from the Research and Analysis phase. Furthermore, crucial requirements are defined during the embodiment phase. Lastly, it was complemented by means of the checklist proposed in the book "Productontwerpen, structuur en methoden"(N.F.M. Roozenburg, 1998).

Requirements

Functionality

1. The product heats up water of an au bain marie container by using residual heat from the air of an ignited kamado with an internal temperature of at least 100 degrees Celsius.
    a. *The product keeps one litre of water at at least 60 degrees Celsius when the kamado is at a constant temperature of 100 degrees Celsius.*
    b. *The product heats up one litre of water from 15 to at least 60 degrees Celsius within 45 minutes when the kamado has an internal temperature of 250 degrees Celsius.*
    c. *The product should provide a way to add boiling water if the product is used at a low kamado temperature, to reach the desired temperature quicker.*
    d. *The product produces enough electrical power by its Peltier elements to continuously power the electronics.*
2. The product must enhance cooking on a kamado.
    a. *The product keeps food warm by heating water, as done in the au bain marie method.*
    b. *The product should stand firmly on the table.*
    c. *With the product placed on it, the table may not bend down more than 15 degrees.*
    d. *The product facilitates a space of 325 by 265 millimetres. The container will be 100 millimetres deep, conform common ½ gastronorm size. This is large enough to fit fits 5 commonly sized spareribs, one complete chicken or a commonly sized brisket.*
3. The product should not outweigh 3 kilograms in an empty state.
4. The materials used in the product that could come into contact with food should be food-safe, meeting Europe's EFSA standards.
    a. *Any electronics that are not food safe should in no way be able to make contact with the food*
5. The product should prevent the user to get burned by the product. Therefore, the maximum temperature of the handles is allowed to be 65 degrees Celsius, which is the maximum allowed temperature for handles, knobs, grips ect. continuously in normal use, made out of vitreous materials (International Electrotechnical Commission, 2019).

Durability

6. The heat recapture segment of the product should withstand a temperature of at least 350 degrees Celsius over a time span of 15 minutes.
    a. *A temperature higher than 350 degrees Celsius can only be achieved by taking off the topcap, so the heat scavenging part is not heated up further.*
7. The product should last for 5 years, with a use of 30 times a year.
8. The product should be able to withstand debris, by either having a filter before the water enters the water pump or by using a filter that can withstand small pieces of debris.
9. The electronics in the product should be able to withstand 100 degrees Celsius and a humid environment.

Price

10. The product has a consumer price of maximum 300 euros, which is about twice the price of a common bain marie.

The Bastard brand

11. The product is designed for the Bastard brand.
    a. *The product should be robust*
        i. *The lid of the product should withstand a fall from the table on grass without any significant damage.*
    b. *The product should fit the visual style of the Bastard*
        i. *The main colours of the product should be dark and mostly shades of black.*
        ii. *The handles should be made out of dark brown bamboo.*
    c. *The product should fit on a side table of a Large Bastard and on an XL Bastard, which has the same table size.*
    d. *The product should stand firmly on a side table, without tipping over or falling off the table if it is hit on the side by a person.*

Wishes

1. The product should be simple and intuitive to use
2. The product should facilitate a way to present food to the table; it should be portable.
3. The user should be able to set a temperature between 20 and 90 degrees Celsius and keep it at that temperature with an accuracy of 2 degrees Celsius.
4. The parts of the product that come into contact with food should be dishwasher proof
5. The product should fit on a table of a Bastard Medium.
6. The product should clamp onto a table of a Bastard kamado
    a. *The product should be easily attachable and detachable from the kamado*
7. The heat recapture segment of the product should attach and detach easily from the topcap
8. The product should give a warming to detach if the product overheats.
9. The use of non-recyclable plastics should be avoided where possible
10. The use of non-commodity plastics should be avoided where possible
11. If the product contains any screws, these screws should be commonly available and as interchangeable as possible.
12. The lid of the au bain marie container should have a place where it can be hung or put if the lid is taken off.

/TOPCAP

To make the topcap suitable for heat scavenging, the outgoing air needs to be concentrated in one outlet. The current design of the topcap, as shown in figure 38 on the left, does not provide such a concentrated air outlet. Neither other brands have a suitable topcap design that has such an air outlet. Fortunately, the company still had a concept of a topcap that centred the air to one place behind the kamado. This concept was not finished yet but could be used. This concept is shown in figure 38 on the right. By redesigning this topcap, a suitable place for the heat scavenging system can be provided.

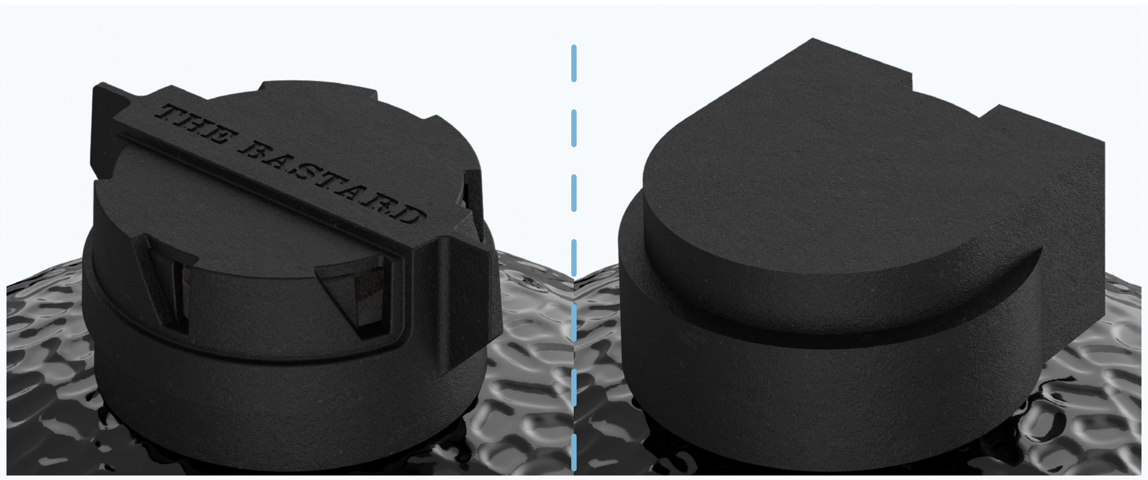


Figure 38. Original topcap versus first concept, which guides the air to the back instead of all around. No worked out solution to setting the airflow was defined in this concept yet.

Designing With Cast Iron

Since the topcap is made out of cast iron, some important design guidelines need to be taken into consideration during its design. The main requirement of a topcap is that it should be designed in such a way that if it is closed, it does not leak any air. The old design did do this, and it became clear why. As seen in figure 38 on the left where the old design is shown, the topcap had "ears" on the side of the shell. This caused uneven cooling after the cast, which caused the round top to pull out of shape. In the new topcap design, the walls need to have an even thicknesses and all sharp edges need to be rounded as much as possible. In the old design, the touching surfaces where not flat but cylindrical, as shown in figure 39. To make sure no air can leak from the topcap, the closing surfaces should be flat surfaces touching each other. Flat evenly thick surfaces usually come out reasonably flat when cast, which makes the chance of leaking air significantly smaller.

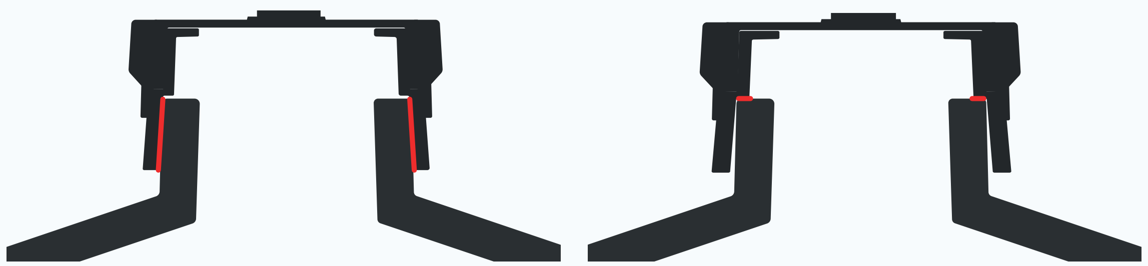


Figure 39. The old closing vs the new closing principle. When flat cast iron surfaces touching each other close off the cap, it is easier to make it airtight.

The First Topcap Concept

In figure 40, the first redesign of the concept can be found. The concept consists of 4 parts; the lower part being the part that slides onto the ceramic with a strip of felt in between to serve as an airtight gasket. On top of this part, the round regulator can be found. It has a small poke pointing towards the user, which is used to configure the temperature setting of the topcap. The third part closes the top off, providing the guided airflow to the back of the kamado, as well as protection from rain falling into the kamado. The last part is the part where heat sinks can recapture the heat, with heated air travelling through out of the kamado. The heat recapturing part is made out of heat fins and a water cooler. This means that the air travels passed small metal fins which absorb heat. The heat then travels through the highly conductive metal to a water cooling block, which dissipates the heat to the streaming water through the block. This principle of transferring heat is based on existing cooling principles in computers.
The heat recapturing part also needs to hold a place for the Peltier element, to as well heat the warm side with the air from the kamado, as cooling it with the water that runs around. A concept of this can be found in figure 41.

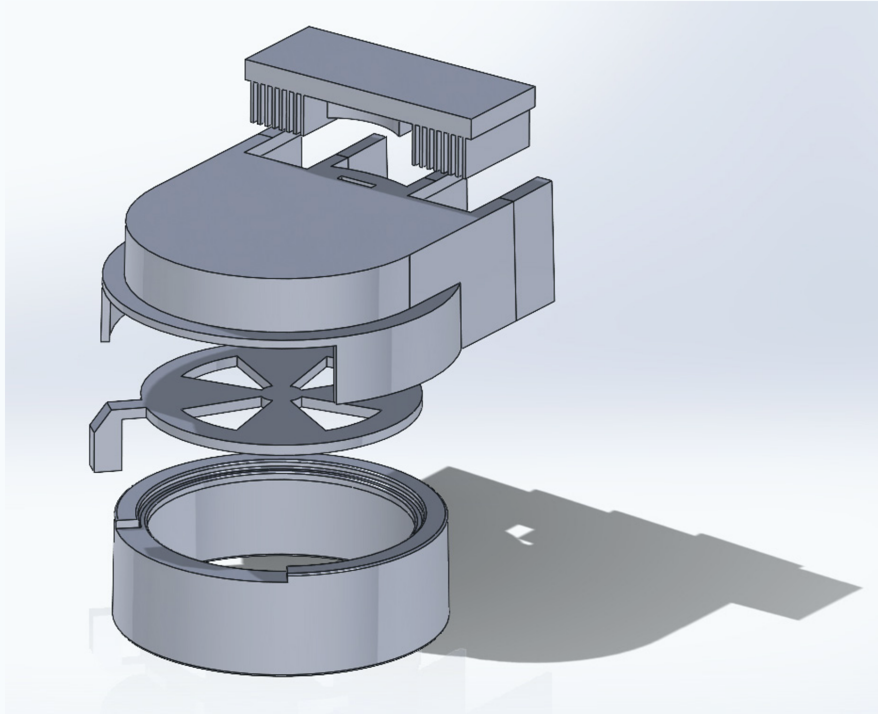


Figure 40. Exploded view of concept 1

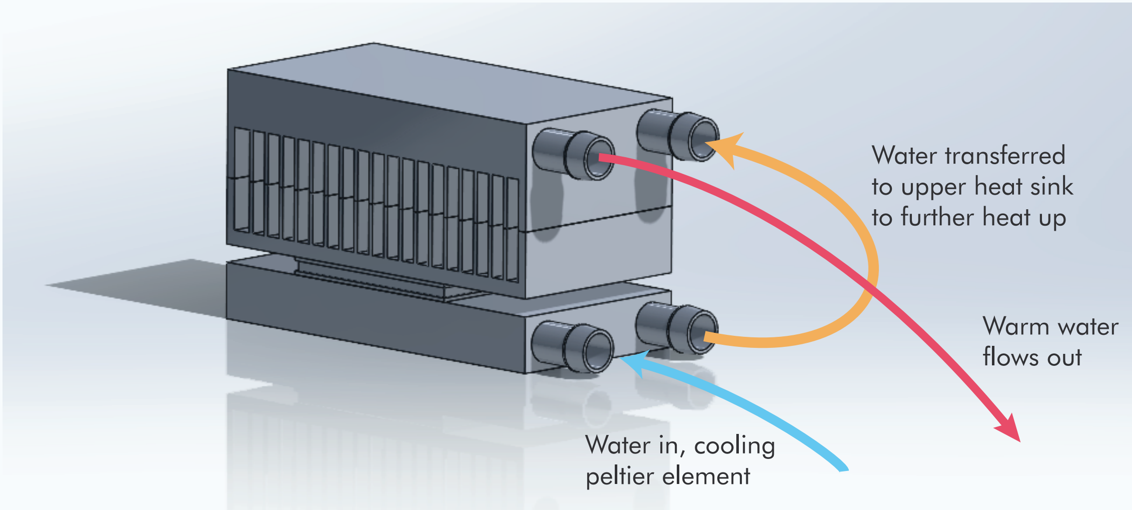


Figure 41. Energy recapturing principle

Designing The Air Valve

The maximum configurable air opening of the topcap should be about the same as the area of the open hole in the ceramic, so the maximum temperature can be reached. Redirecting the airflow to one side is expected to slow down the airflow however. To see the exact effect of this however and tweak it in a desirable way, the product needs to be made out of a temperature resistant material and must be tested. Based on the results of the test, the design can easily be tweaked to make the holes slightly bigger or smaller. However, we expect the airflow settings to behave comparable to the old design.

The accuracy of the airflow set by the user can be chosen by design. The bigger and fewer holes there are, the bigger the range that can be set by the user is. A few options are logical because they make sense geometrically wise, which are shown in figure 42. For the 90 degrees poke range option was chosen, since our persona cares about preciseness so an exact setting is important. Since the user is using the au bain marie product, the user is putting a lot of effort in their dish, hence he wants to tweak the temperature as exactly as possible. This decision will increase the precision of the set temperature drastically, compared to the old topcap design. The range could also be doubled, but that would cause in an oversized, unclear range of the settings of the airflow.

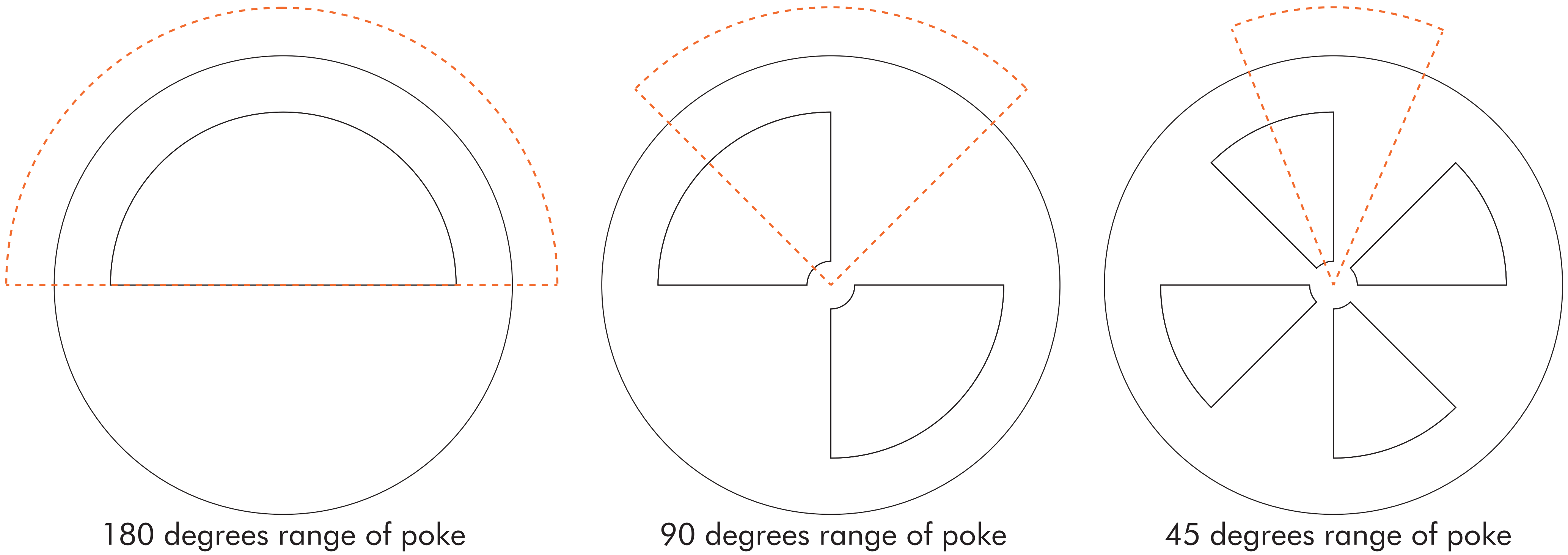


Figure 42. Possible temperature setting ranges of the topcap

/Electronics

To make the system functional and efficient electronically, electrical components need to be analysed and chosen. Since the power source used should work optimally to provide enough power for all use cases, an efficient configuration of the electronics is crucial.

Thermal Electric Generator

To power the system, a Thermal Electric Generator will be used. In this case, the GM250-127-14-10 by European Thermodynamics was chosen, due to its high temperature resistance and its high power capacity at low temperature differences. This module has similar specifications to the one used in the Biolite CampStove 2 (bioliteenergy, 2017). Their engineers were so kind to send a data graph of the performance of their Peltier element. Although it is not possible to show the graph that was send, the performance of the GM250-127-14-10 was similar to the one that was used in the Biolite CampStove 2. This high-end TEG is necessary in the design, because of the limited space available and because of the high temperatures it will encounter. The matched load power output of the element is shown in figure 43.

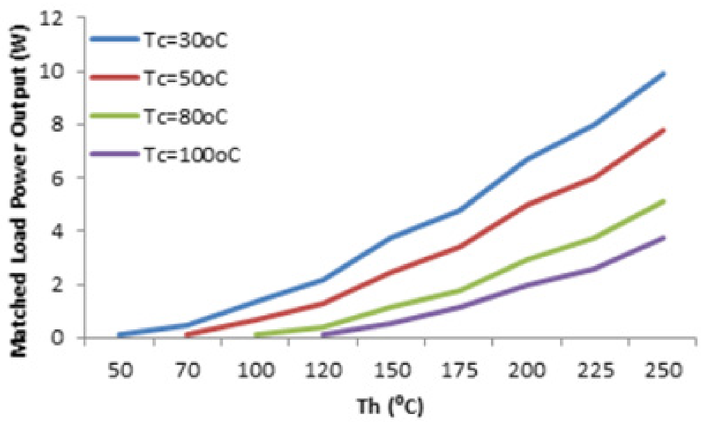


Figure 43. The Matched Load Power Output of the chosen TEG (European Thermodynamics, 2019)

Thermal Interface Material

To ensure maximum performance of the Thermal Electric Generator, the heat flow between the materials should be optimized. The first principle which is widely used is to place a Thermal Interface Material (TIM) in between the parts that should conduct well. As seen in figure 44, at microscopic level small blobs of air can significantly slow down the heat flow which is why a TIM is needed.
In this case, the TEG should not be attached with heat paste which is a common TIM in for instance CPU coolers, but with a graphite sheet. The reason for this is that thermal greases can dry out at higher temperatures, especially in systems that require very long lifetimes (European Thermodynamics, 2019). European Thermodynamics states that the thermal performance of graphite sheets is approximately equivalent (<2% difference) to a thermal grease under adequate clamping pressures. They also state that clamping is an essential step in designing the system, since failure to clamp a thermoelectric module can lead to performance losses of 20% or more. The key here is to choose the right clamping load, to clamp evenly and to reduce parasitic thermal losses.

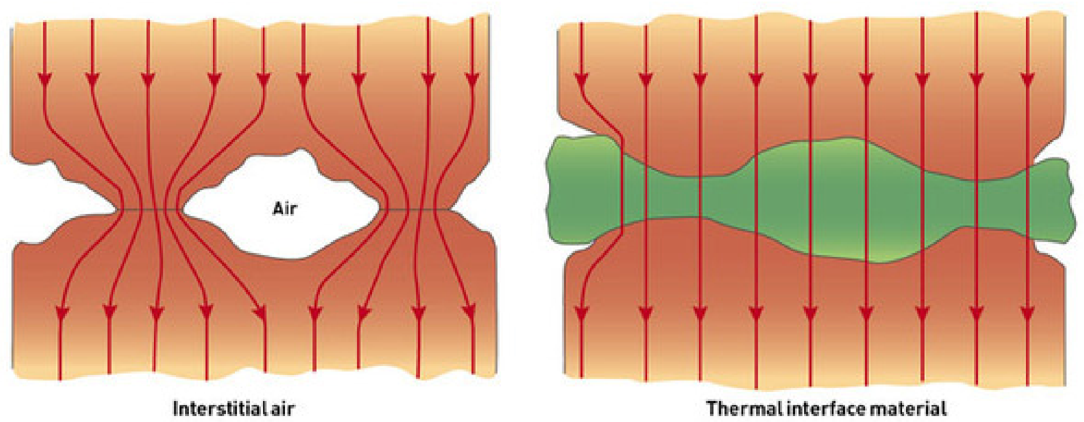


Figure 44. The effect of Thermal Interface Material (All about Thermal Interface Material, 2009)

Battery

The system needs a battery that is charged during excess power, and saves power to use the interface and pump the water at the moment that there is too little power available. This is firstly because of the function of the pump to cool the Peltier element, to ensure maximum performance. As soon as the Peltier is cooled on one side, the Peltier element should produce enough power to run by itself in most situations as described in the program of requirements. Also during start up, the pump may require more electricity to overcome the extra resistance to get the water flowing, which could require more power because of air bubbles in the system.

A common rechargeable AA battery was chosen. Generally, the options are a lithium ION battery which is used in many electronic products because of its high energy density, or to use common AA batteries which have less energy available. However, using 4 rechargeable AA batteries with a total of 4.8 volts is a better, more widely available and safer option because they can generally handle more extreme temperatures and humidities. They can also easily be replaced in the rare case that they would run flat completely. In the case of a lithium ION battery, a flat battery is more dangerous with in extreme cases even risk of exploding. And if it does run flat, it needs an external charging system which needs to be delivered with the product, while recharging stations for AA batteries are commonly available.

Choosing A Water Pump

In order to not drain the battery during long lasting situations that little power is available, a low power water pump should be used. Both a centrifugal as a vacuum low power pump was tested on displaced water per wattage used. Also, they were tested on the minimum voltage it needed to overcome the static friction of getting the water flow started. The data found in Appendix F showed that although a centrifugal pump uses more power to start the water flow initially, it displaced significantly more water after the water was flowing using the same power. Because batteries are used, the energy to overcome this static friction is available which makes the centrifugal pump a logical choice.

Designing The Circuit Board

For such an electrical circuit to function optimally, it is crucial for all voltages to be matched as much as possible. Since we are working with a variable power source, a power converter is used to bring the power up or down to a set desired voltage which matches the batteries, as well as the control circuit. A good converter that is designed to work optimally at the most occurring voltages should be chosen. The control circuit in this case is the Arduino Nano, which has an operating voltage of 5 volts and only draws 19 mA, which comes down to a power usage of 0.095 watts. The voltage coming from the Peltier element will be regulated by a buck converter, which can either step down or step up the voltage to the desired 5 volts. At this 5 volts, both the battery as the Arduino function properly (Technobyte.org, 2016).

The chosen waterpump works on 4.5 volts and is rated to only use 0.91 watts of power. During testing, we found that they also start pumping water around when only 0.65 watts is available, pumping a lesser amount but still sufficient. Furthermore, a 7 segment display was chosen to communicate the temperature to the user. In the 7 segment display, each of the 7 LEDs draw about 15mA to work properly (Electronics Tutorials, 2014). On average, 5 out of 7 are on, which gives a total of 75mA or 0.375 watts. If we take an estimated 10% energy loss in the circuit into account, the total circuit would need a continuous 1.23 watts to operate.

Lastly, it is important that the circuit has a button to completely shut down the system when it is not used, so unnecessary drainage of the battery is minimalised. Thus, the batteries will last longer and still have power when the product is starting up.

The final design of the circuit board is shown in figure 45.

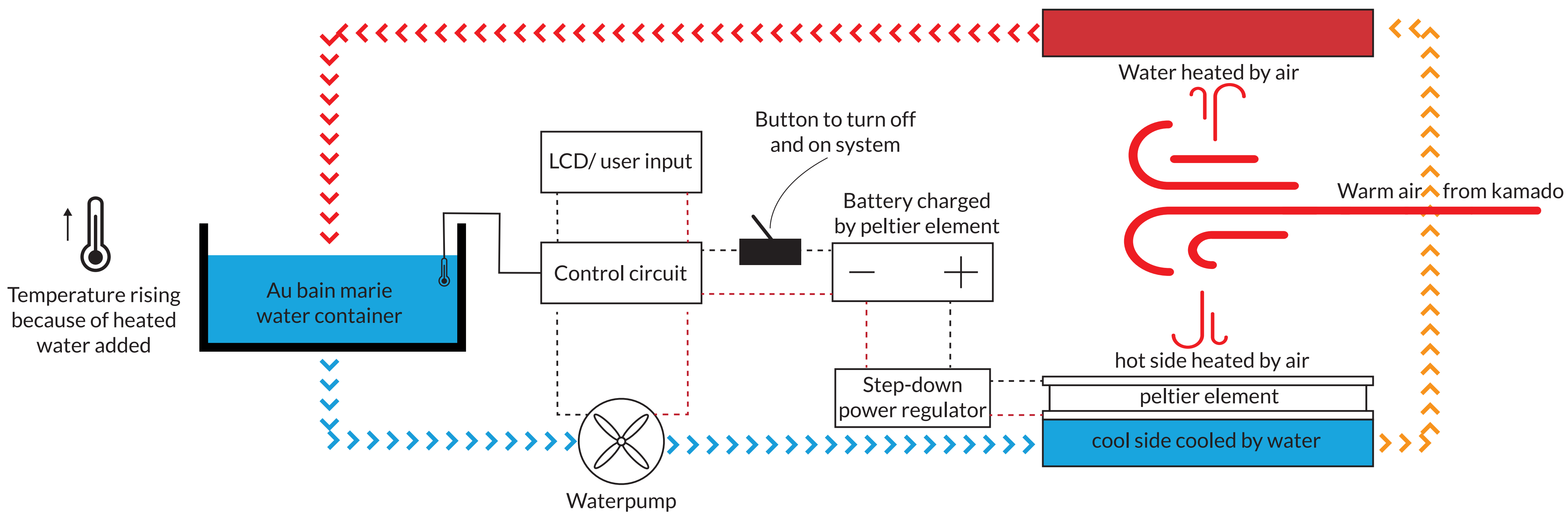


Figure 45. Final envisioned energy circuit

/PROTOTYPING TOPCAP DESIGNS

We have already proven that the heat capacity of a kamado running at 250 degrees Celsius is sufficient to deliver enough power to the au bain marie in prior experiments. The next step is to redesign the topcap, such that it functions efficiently at all temperatures. Firstly it must provide a single air outlet, centring the heat energy to one position where it can be captured. Secondly, a way to configure the topcap temperature setting was designed and tested. Lastly, the electrical energy output at low temperatures is measured.

Findings From The First Prototype: General Functionality

By making a 3d print, the general functionality of the second iteration was tested. A picture of the 3d print placed on the kamado air outlet can be found in figure 46. The handle to set the valve at a certain temperature setting worked well, although the small handle could stick out a little more to make it easier to control for the user. Indications on the topcap at what setting it was set should be engraved in the lower part, to make setting it more clear to the user. The topcap concept was rede-signed to facilitate one air outlet. This iteration makes the heat recapture part easily detachable, by merging it into assembly which is placed onto the topcap. In this model, the top part was produced as a single part, which makes it hard to cast in one piece. A solution was to make a detachable part for it, where the heat recapture segment is made into one assem-bly. This was implemented in the next iteration

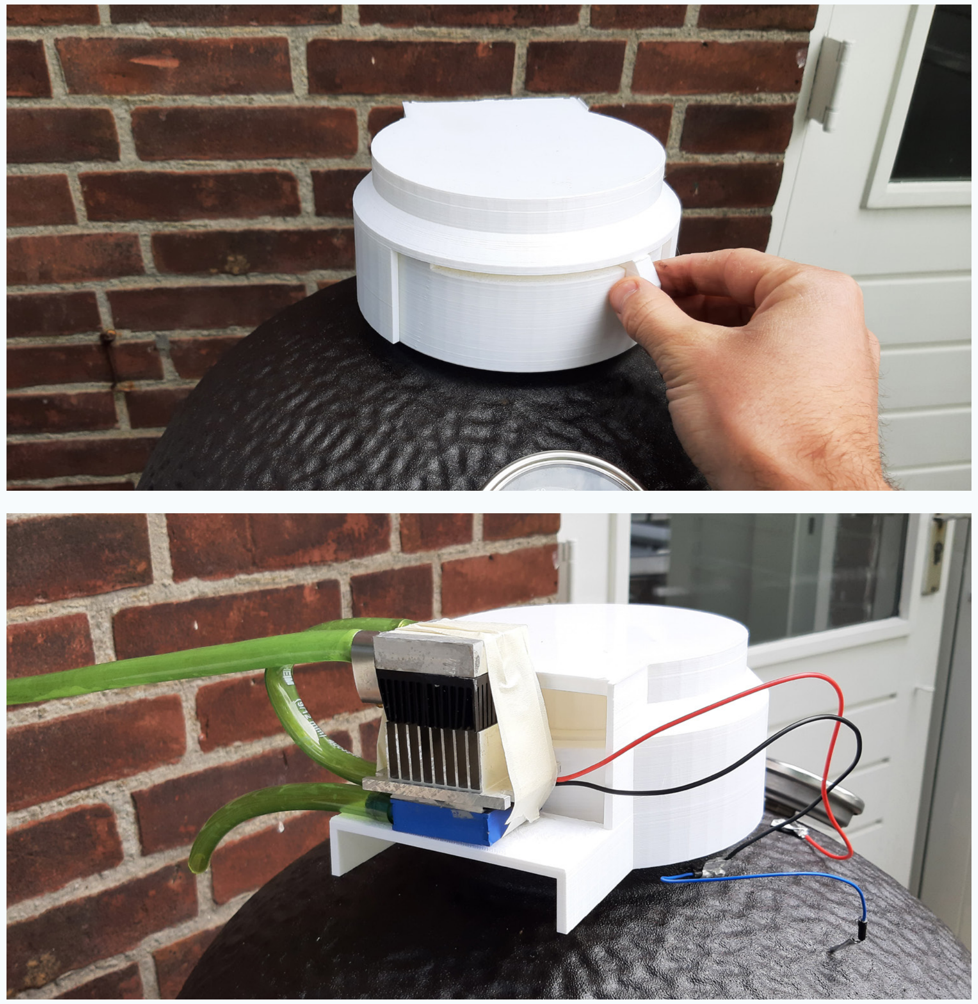


Figure 46. Testing the first prototype, placing a dummy heat recapture part on it

Second Prototypes; Findings And Iterations

The goal of this test was to see if there was enough energy available to run a low power centrifugal water pump, at a low kamado temperature of between 100 and 150 degrees Celsius. For this 3d print, a more temperature resistant filament was chosen; GreenTEC pro carbon by Extrudr. This filament has its VICAT softening point (ISO 306) at 165 degrees Celsius, which makes it suitable to test on the kamado at lower temperatures. The system contained a single high performance Peltier element.

The heat recapturing part was screwed together firmly, to guarantee a good thermal connection between the heat fins, the Peltier element and the water cooling block. Heat paste was placed in between to improve the thermal transfer even further.

The system was tested to see if it was suitable to meet the first temperature requirement; keeping water at 60 degrees Celsius while it is running at 100 degrees Celsius. The result was that the pump only ran a little, but not nearly enough to pump the water up through the water cool block. This was in line with the expectations of “Choosing a water pump”. The amperage peaked at around 0.124 A, at a kamado temperature of around 140 degrees Celsius. To reach a higher power output, in the next iteration a second TEG should be added. The air outlet needs to be redesigned to facilitate the room for the second TEG.

Figure 47. Testing the prototype with the waterpump attached

Findings From The Third Prototype

To make this model more efficient giving it a higher electrical power output, different parts were changed. Firstly, a second TEG was fit into the air exhaust, increasing the width of the part. Secondly, the base plate of the heat fins part was thinner, so the heat had to travel a shorter distance to the TEG. There were more separate and thinner heat fins, which increased the total surface area touching the air and increased turbulence which again increases heat transfer. Thirdly, the container of the heat reclaim part was made out of two parts, so the top part could be placed on it and hold it all together firmly. On the picture at figure 48, the tested prototype can be found. There are more water tubes than necessary in the final design, but this was because there was no suitable water cooling block available at the time of testing, so the water had to travel through two separate water blocks.

The results showed higher power, with the voltage peaking at 1.64 volts. The amperage was also higher than the previous test, peaking at 0.137A at 120 degrees Celsius. In total, this would give 0.23 watts to deliver to the pump. For the centrifugal pump to start however, 0.62 watts of power are needed. This means that the system should work such that the excess energy that is generated during operation at high temperatures should compensate for the too little energy that is generated at lower temperatures. The batteries in the system will serve this purpose.

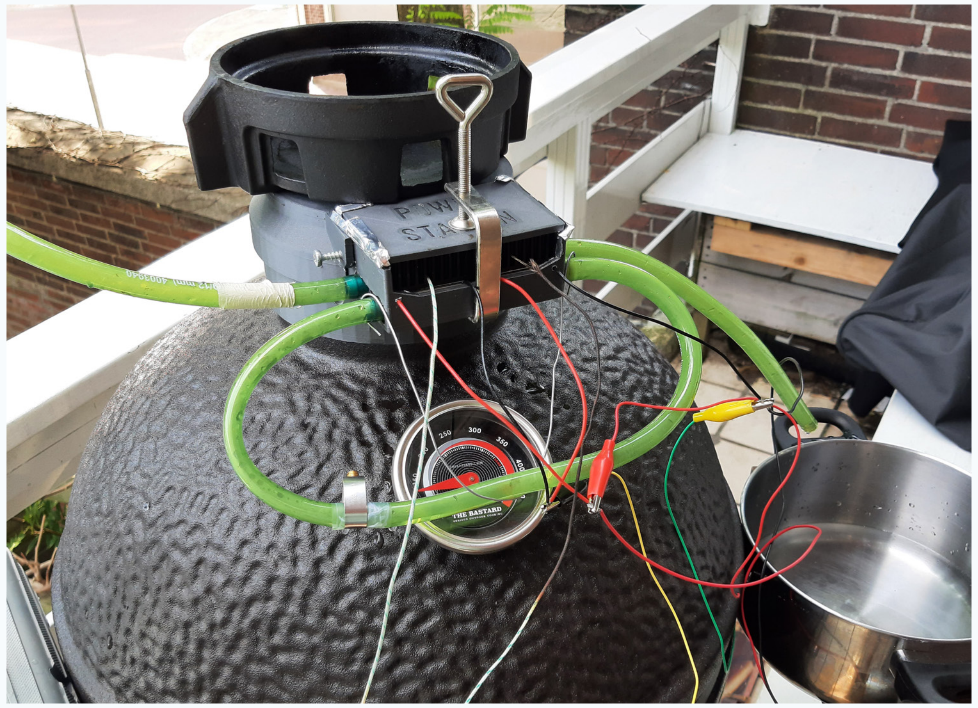


Figure 48. Testing the third prototype

Testing The Electricity Production Capacity Of The Peltier Elements At Higher Temperatures

The Peltier element is expected to produce enough energy at higher temperatures to compensate for the limited power available during lower temperatures. To test this hypothesis, another experiment was conducted. Where low temperature experiments are conducted with the 3D printed topcap prototype, this data was gathered using a cast iron topcap which was reused from a prior test because the 3D print would not be able to resist these high temperatures. The test setup contained a kamado with an internal temperature of around 250 degrees Celsius. The air was guided past two separate heat fins, each attached to a Peltier element. The Peltier elements were cooled with two water blocks, with the water being about 40 to 45 degrees Celsius. The water was pumped around by the Aqua-Flow 100, powered by normal AC power. The volume of the heat fins was similar to the one in the proposed final design. Because a load needs to be attached to the electrical circuit for accurate readings, the water pump proposed in "Choosing a water pump" was attached and put into water to give it a load. In this electrical circuit, both the voltage and the amperage were measured. The amperage gave 0.25 A, and the voltage an average of 15 volts. This translates to a continuous 3,75 watts of power during kamado operation at 250 degrees Celsius.

Figure 49. Test setup Peltier element experiment

“Face” Of The Topcap

The topcap outlet reminds of a car grill because of the rhythmic vertical heat sinks placed there. To make the outlet slightly more aggressive and less blocky, the sides are slightly chamfered as done at the BMW shown in figure 50. In the interviews, the vendors mentioned that the Bastard buyer is someone that would drive a BMW, which means it is a good fit as a reference. As the au bain marie container contains a chamfer if you look at it from the side, it also adds to the notion of making it a product family.

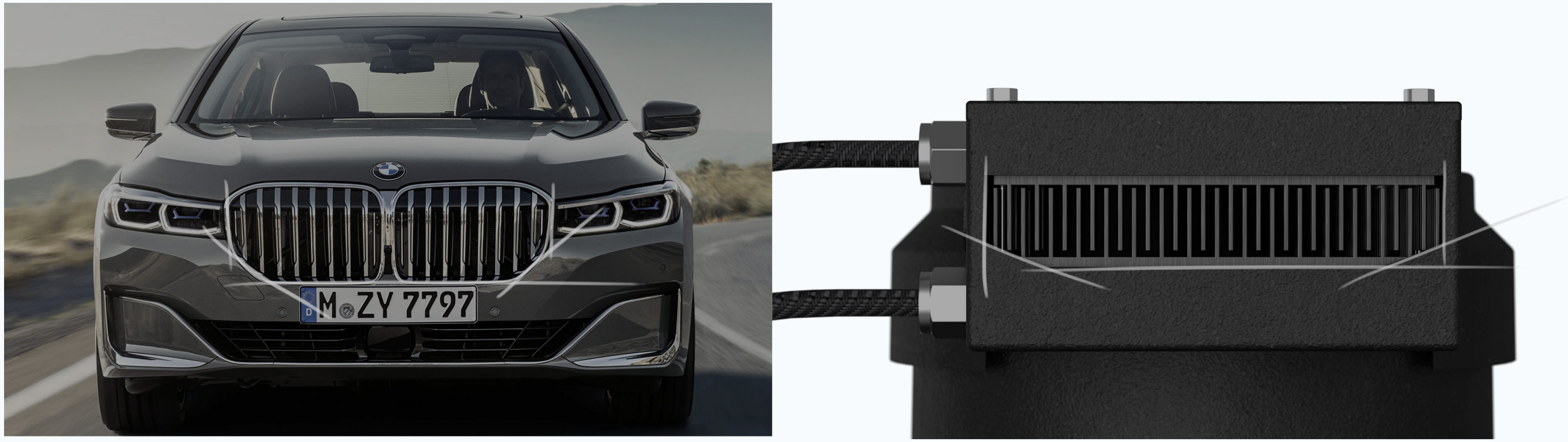


Figure 50. Comparing the grill of an BMW to the “grill” of the topcap

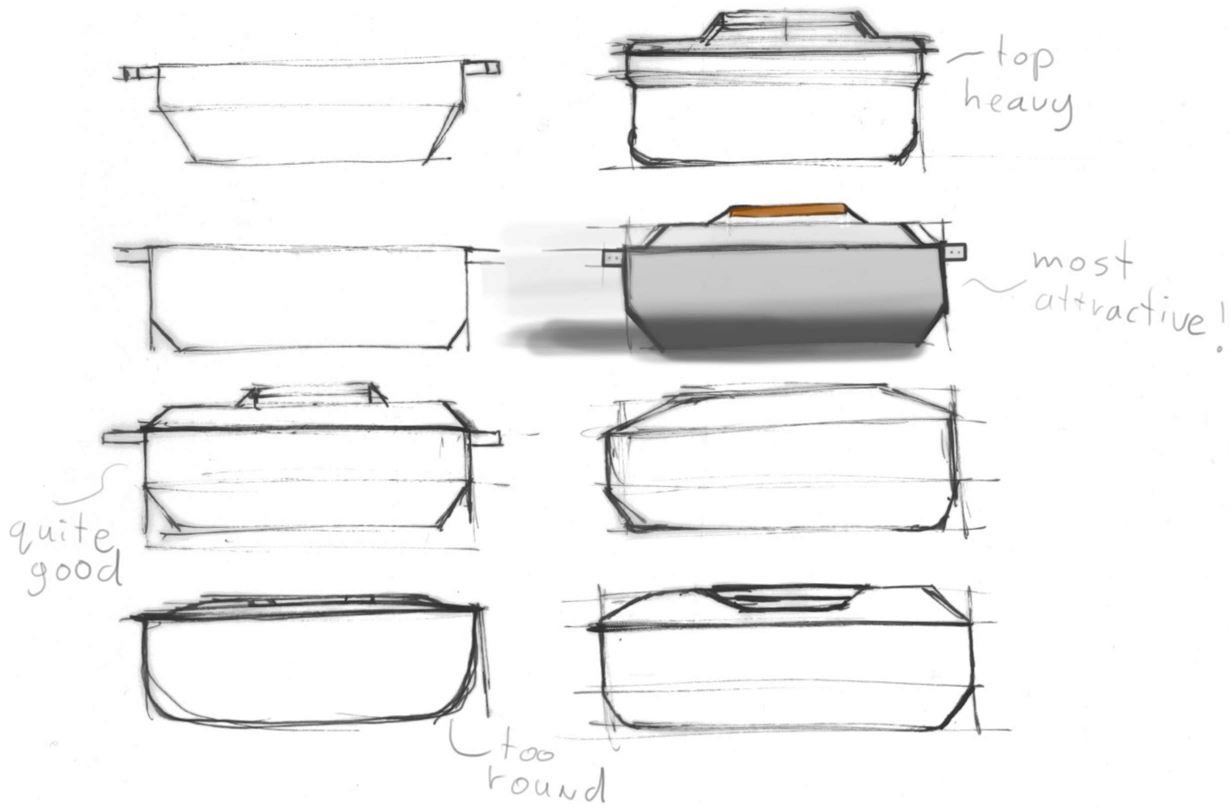
Testing The Heating Capacity Of The Kamado At 100 Degrees Celsius.

Since we found that the temperature drops significantly at the topcap when running the kamado, another test was important to test the heating capacity at lower temperatures. One of the requirements is that the kamado should be able to keep one litre of water at 60 degrees Celsius, at the moment that the kamado has an internal temperature of 100 degrees Celsius. The Peltier elements were taken out of the third model and a water pump was attached. Then a litre of water was put into an insulated bottle with a heat loss of 4.65 watts. The water pump heated the water with around 3 watts, which means that there was a total heat loss of 1.65 watts from the test setup, apart from the influence of the heat capture setup. The results were clear; the temperature of the water could not be held at 60 degrees Celsius, but dropped to around 50 degrees Celsius and stayed around there. However in this test setup, less heat loss is expected compared to the actual product which has a bigger surface area. Thus we assume the temperature that the water can be held at between 40 and 45 degrees Celsius.

It is an important finding that this means that in some rare situations, the au bain marie is unusable for the user. This could be in the case of preparing a brisket, which needs to sit for many hours at the same low temperature of 100 degrees Celsius. If in this case the au bain marie stays at 40 degrees Celsius, it would not be very usable because you want to deliver food at a minimum of 60 degrees Celsius. However, most dishes require cooking at higher temperatures, or at least require a short shear at the end of the cooking process which is done around 260 degrees Celsius. We found that as soon as the temperature goes up the heat capacity increases drastically, so the water should not take long to rise from 40 to the required minimum of 60 degrees Celsius.

/AU BAIN MARIE CONTAINER

Firstly, the overall look and feel was defined by the visual identity collage presented before. From here, a silhouette study was done presented in figure 51 and it became clear that the container needed some blunt corners to make it attractive and Bastard like. Also, I chose to add the bamboo handle as found on the kamado itself, to give it a strong connection to the product family.



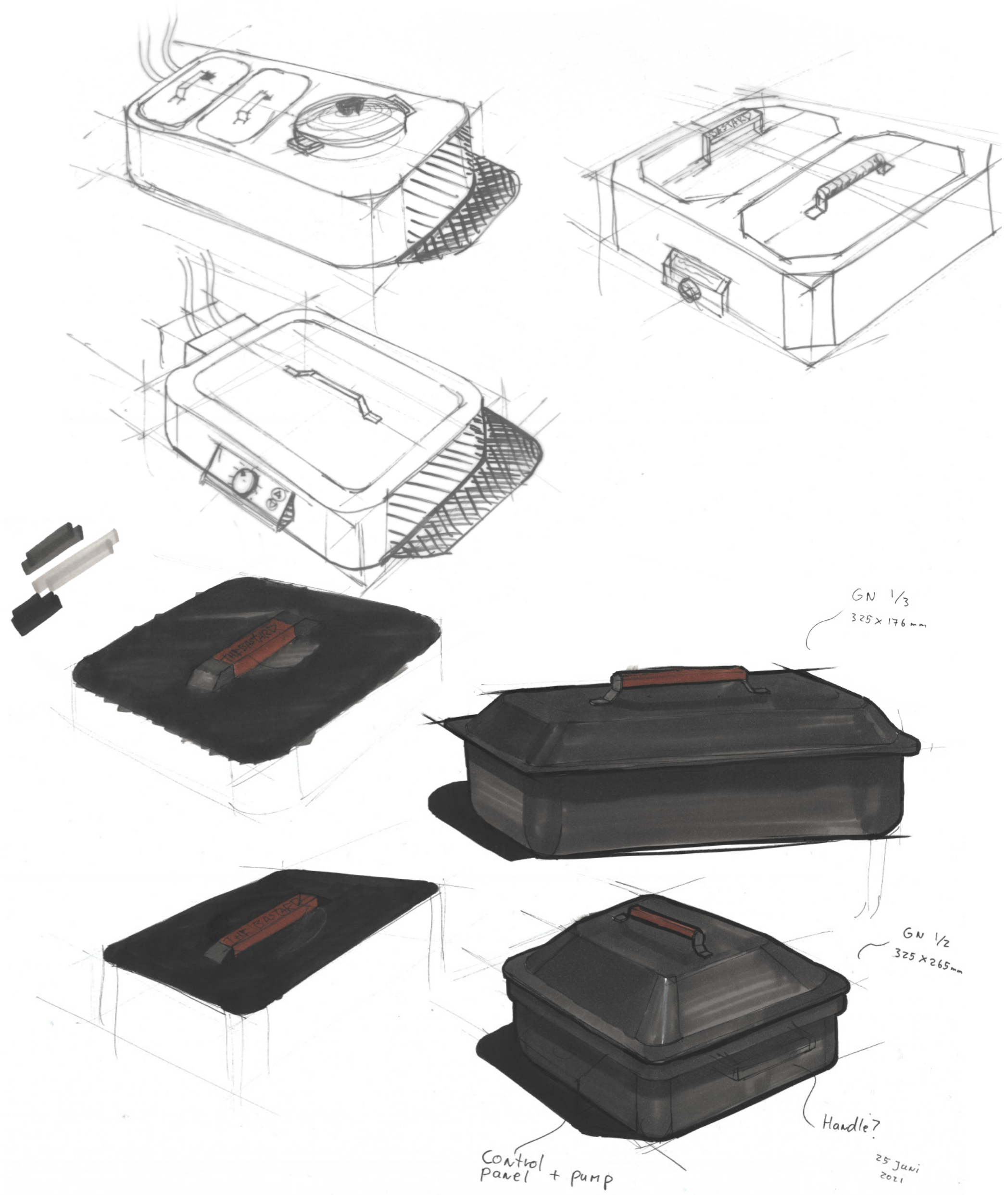


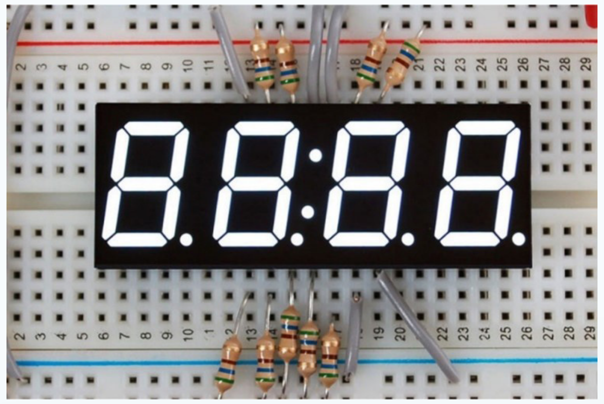
Figure 51. Multiple form studies on the au bain marie container

User Interface

The user interface has to be placed on the au bain marie container, in a housing. This housing should also hold the pump, the electronics, tubing and a place for the batteries. The housing should fit on the au bain marie container, practically as well as visually.

The first idea was to make the controller into a big moveable handle, like a fighter pilot revving up his engines. Although this might be an attractive, big and powerful interaction with the product which suits the Bastard, this would become too big and too unpractical. Also, the control should be precise, which fits our persona. That is how the eventual interface is a knob, which communicates to the user clearly. The interface should be minimal and functional, fit the bastard overall visual style and it must give the user the ability to carefully set and monitor the temperature of the container. The idea came up to place a screen inside a knob, mimicking the thermometer of the Google nest. This gave the opportunity to communicate a lot of information to the user in a fully customizable way. Such a screen would quickly become too expensive however, so a more cost effective solution should be found. Therefore, an 7 segment display is an option that can both be stylish and cost effective. It would also consume significantly less power compared to a screen and it would be a good fit to the overall style of the Bastard. An example of a 7 digit display component can be found in figure 52.

In the 7 segment display, the current temperature would be displayed. The ring around the display contains an orange arrow which points to the set temperature. Small LEDs are around the temperature indicators, which communicate the temperature with an orange indicator. This way, the user can intuitively see the orange light climbing to the set temperature. The knob would consist of an outer part that would turn, and an inner part that would be static, so the numbers do not turn around but stay straight. The knob points to the set temperature which is printed on the housing, with the lowest setting being cold and highest very hot. This is a bit blunt, which suits the bastard style. A concept of the display can be found in figure 53.



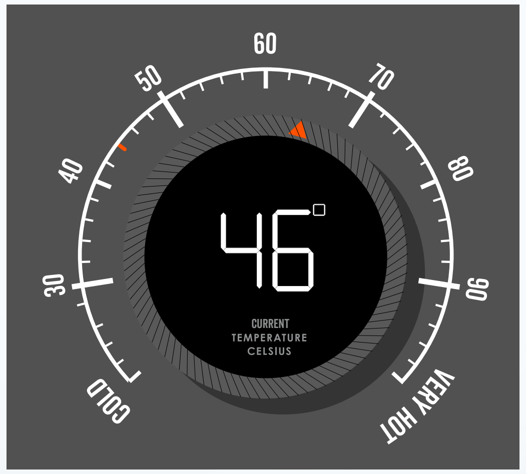


Figure 52. Left: A 7 segment display (Kiwi Electronics, 2021)

Figure 53. Right: A concept of the user interface

The Feet Of The Container

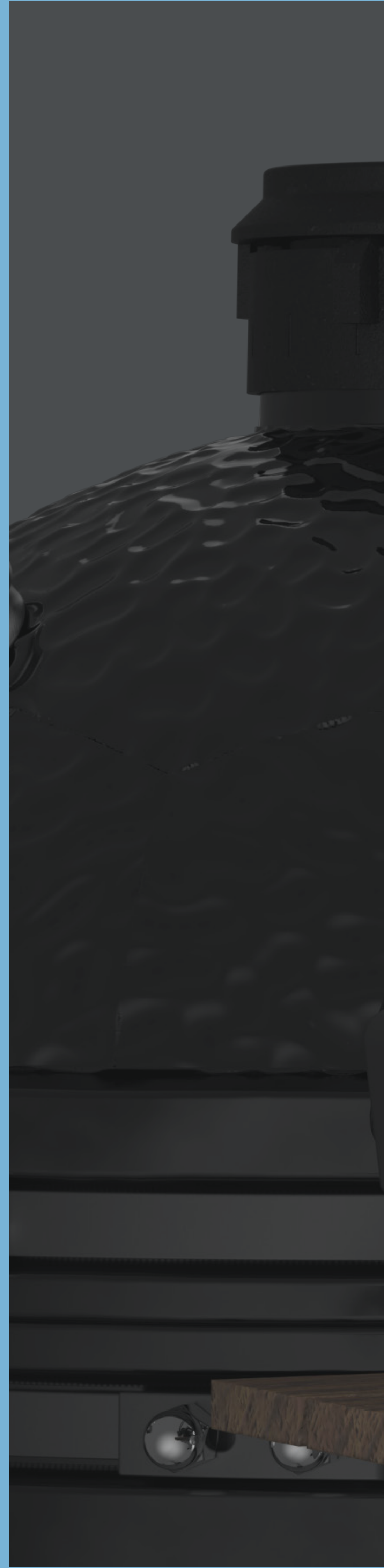
As the program of requirements describes, it is important that the au bain marie stands steadily on the table without tipping off easily. To prevent this, small rubber feet on the bottom of the product will minimize any sliding of the container. Further adding to the stability is the weight of the water which is concentrated low in the product; a low centre of gravity will further increase stability of the product.

Water Container

The container was designed to hold a little under one litre of water, which when heated up has a sufficient heat capacity to steadily keep a dish at a desired temperature while not making the container unnecessary heavy. Verifying this, the total water volume came down to around 0.7 to 0.9 litres of water, depending on how far the user fills up the container. A minimum and maximum indicator on the inside of the container will tell the user how much water to put in.

Final Product

In this phase, the final product is presented. The different parts and some essential design choices are highlighted. Furthermore, user scenario drawings explain the use of the product step by step.

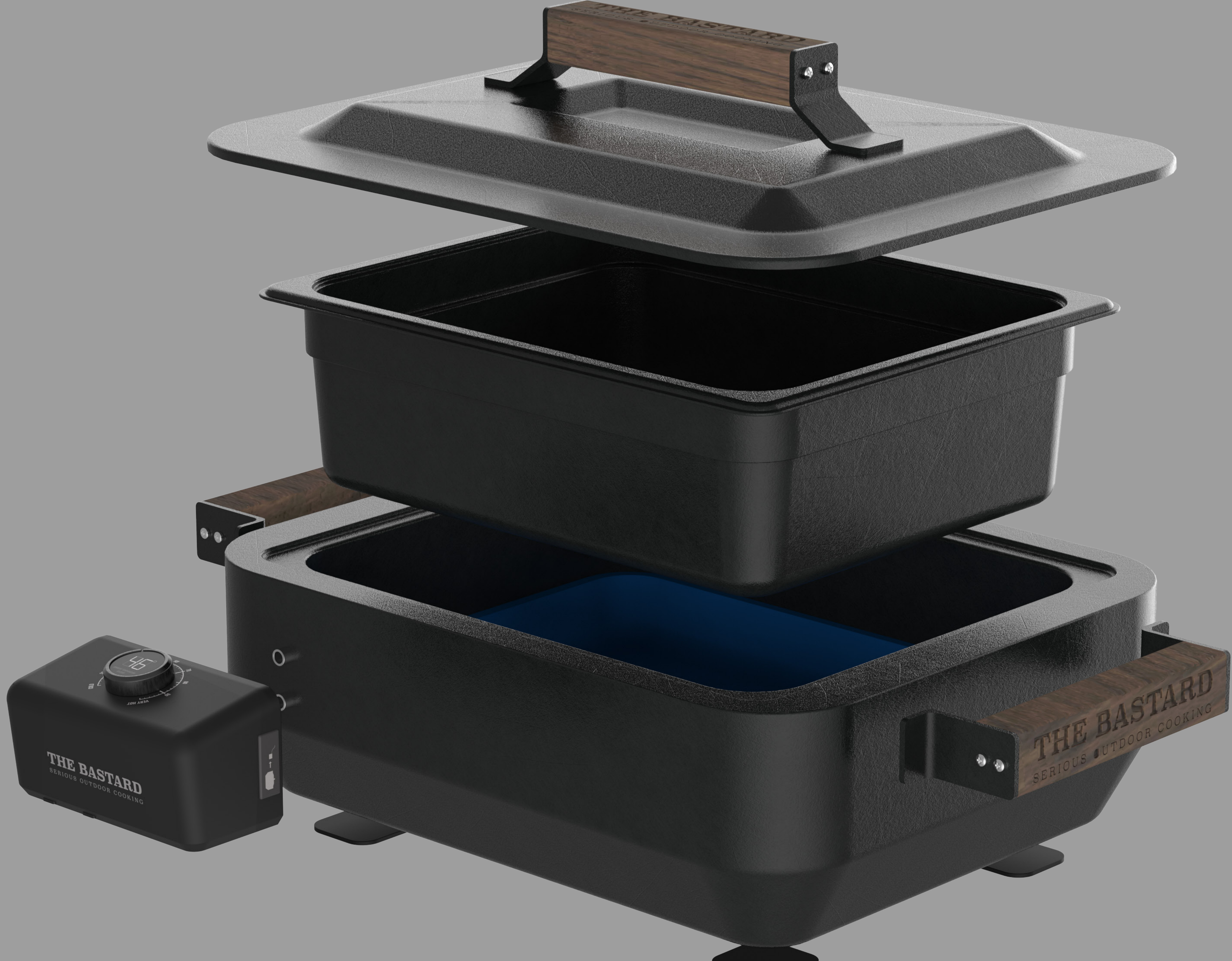


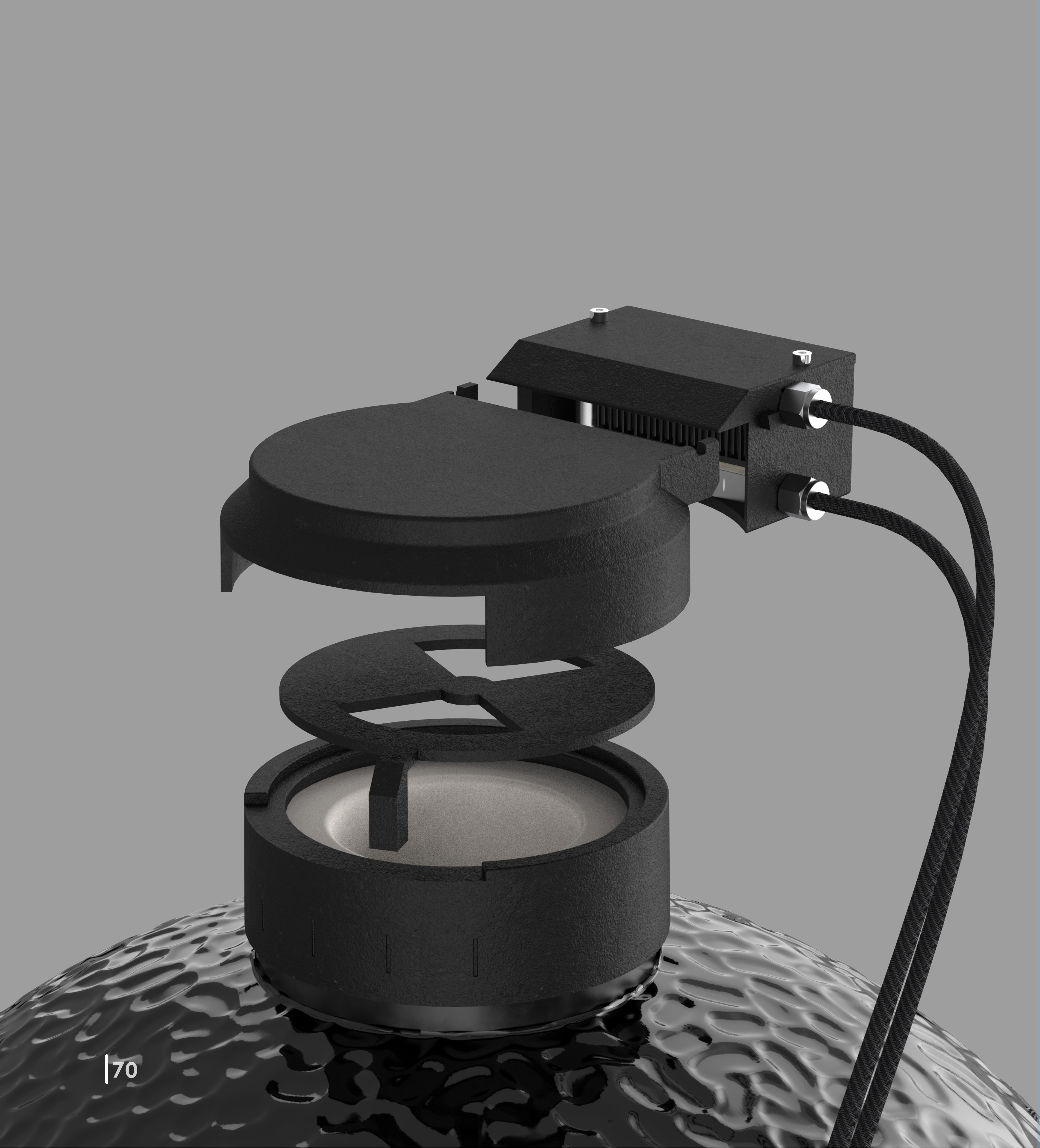

THE BASTARD
SERIOUS OUTDOOR COOKING
THE BASTARD
SERIOUS OUTDOOR COOKING

Au Bain Marie

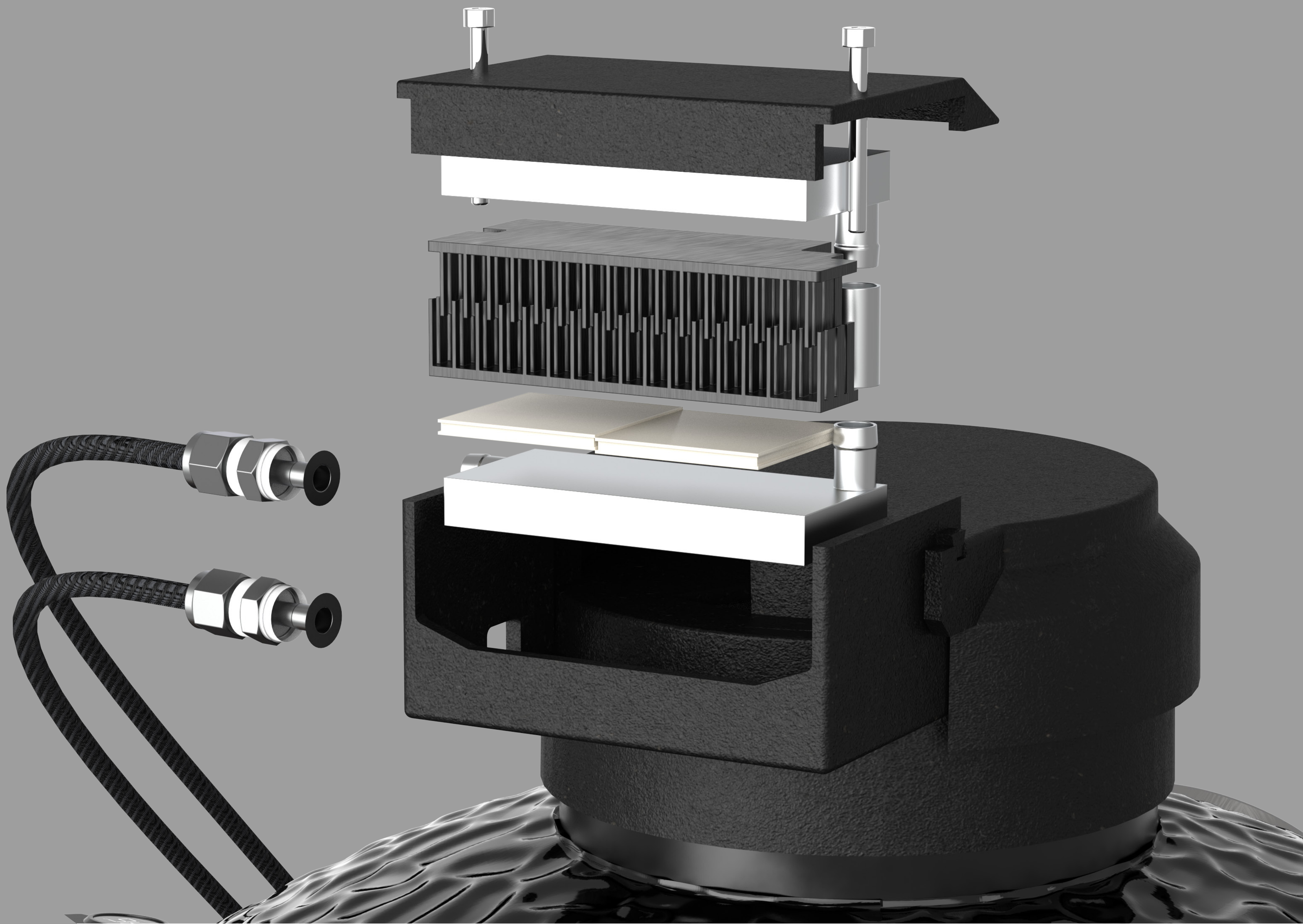
The au bain marie is placed on one of the side tables of the kamado. It is attached to the topcap by the interface, which is easily detachable with a button. The hoses are covered with a fabric mantle which both give its a distinct look as give it extra insulation to keep it cool to the touch.

The lid has a small hook attached which makes it easy to put away the lid if food is put in the container.


THE BASTARD
SERIOUS OUTDOOR COOKING
THE BASTARD
SERIOUS OUTDOOR COOKING



Topcap
The shell of the topcap is made of cast iron, designed to minimize any leaking air when the topcap is closed. The heat recapture part is slid into the topcap by two simple pins. The internals of the heat recapture segment are helt together by two bolts. Small springs are added to the bolts to guarantee proper clamping of the parts which ensure a high efficiency of the heat transfer over time. By only using two bolts, assembly and disassembly is kept simple.

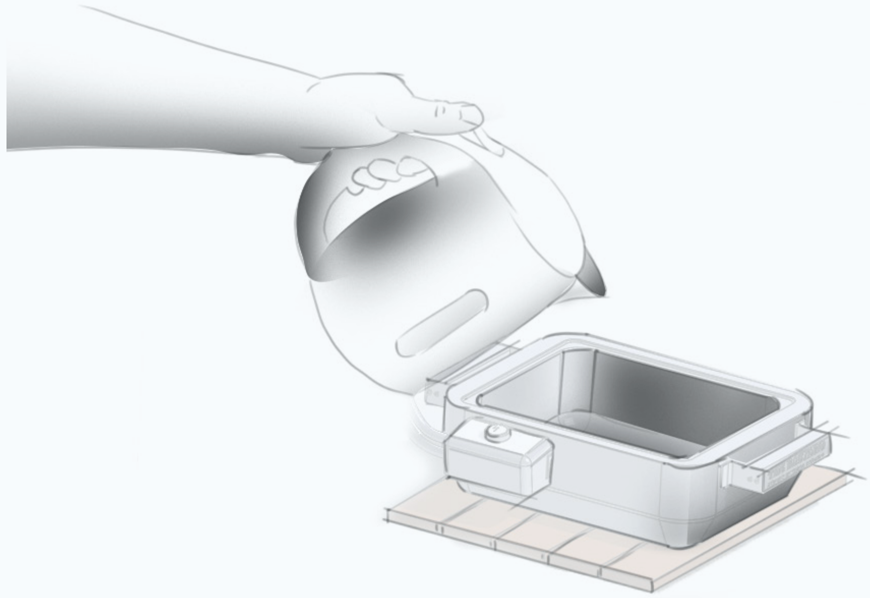


Interface

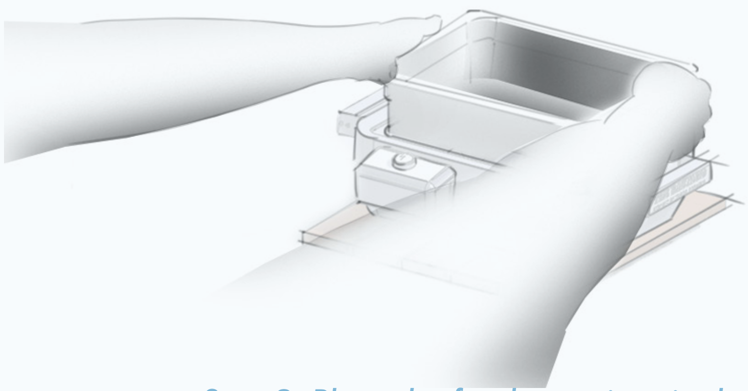
The interface gives the user the ability to set the desired temperature, and communicates the current temperature via the screen. By using the 7 segment displays, the display could be clean, energy efficient as well as low-cost. The knob to deattach the interface is highlighted with a simple icon which communicates its use. The interface holds place for the knob, the waterpump, a temperature sensor, a printed circuit board, the attach mechanism and the batteries.


CURRENT TEMPERATURE
CELSIUS
COLD
70
80
90
VERY HOT

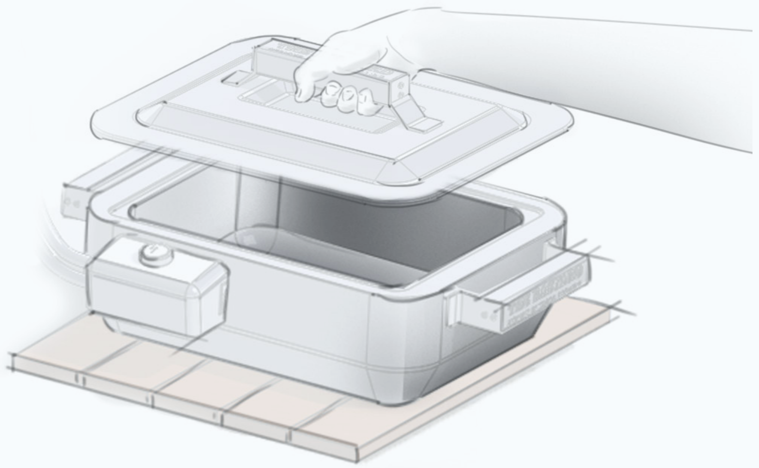
/USER SCENARIO



Step 1. Fill the container with (pre-heated) water



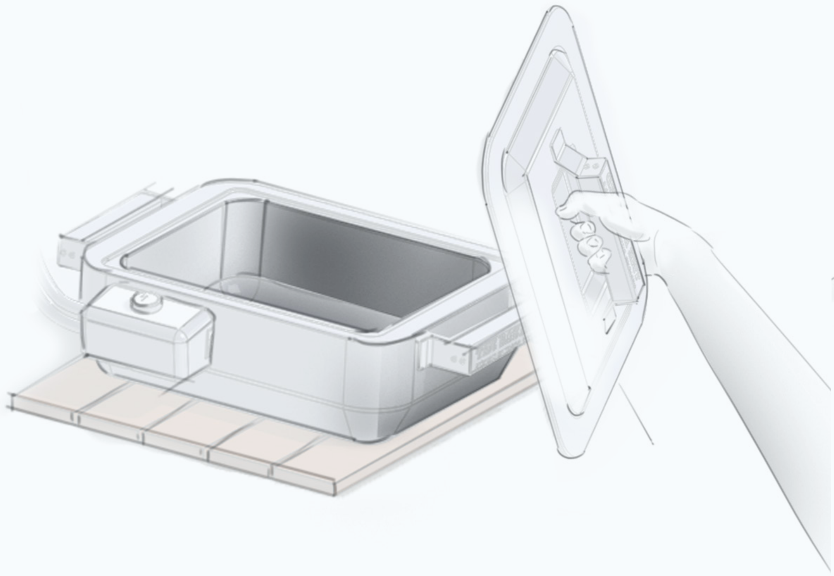
Step 2. Place the food container in the water



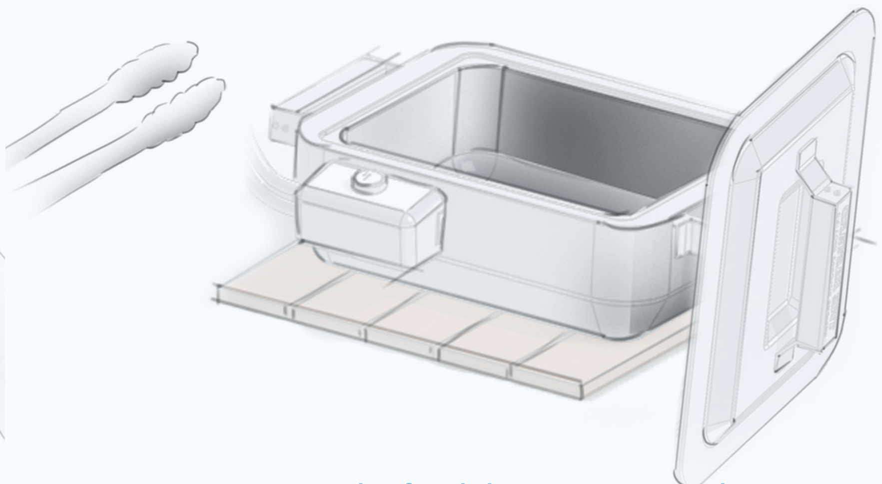
Step 3. Place the lid on the container

Step 4. Set the desired temperature

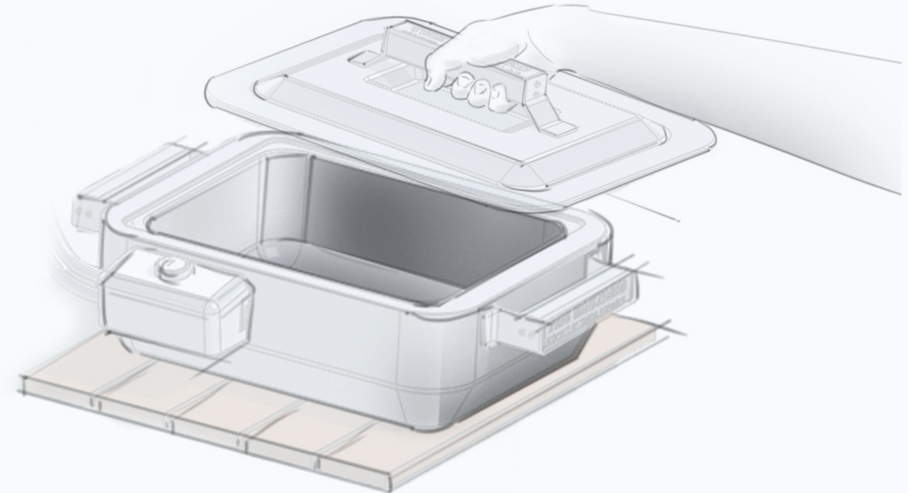
Step 5. Cook your food on the kamado barbecue



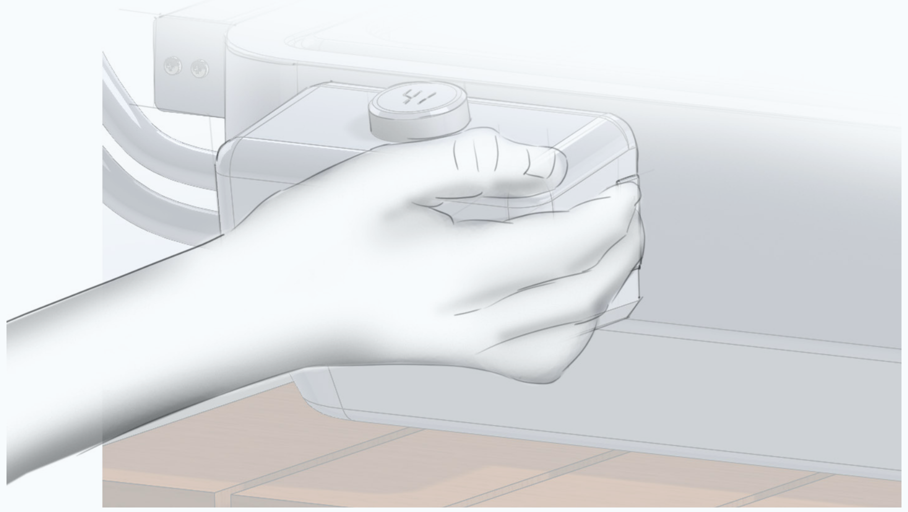
Step 6. Take off the lid, place it on the side handle



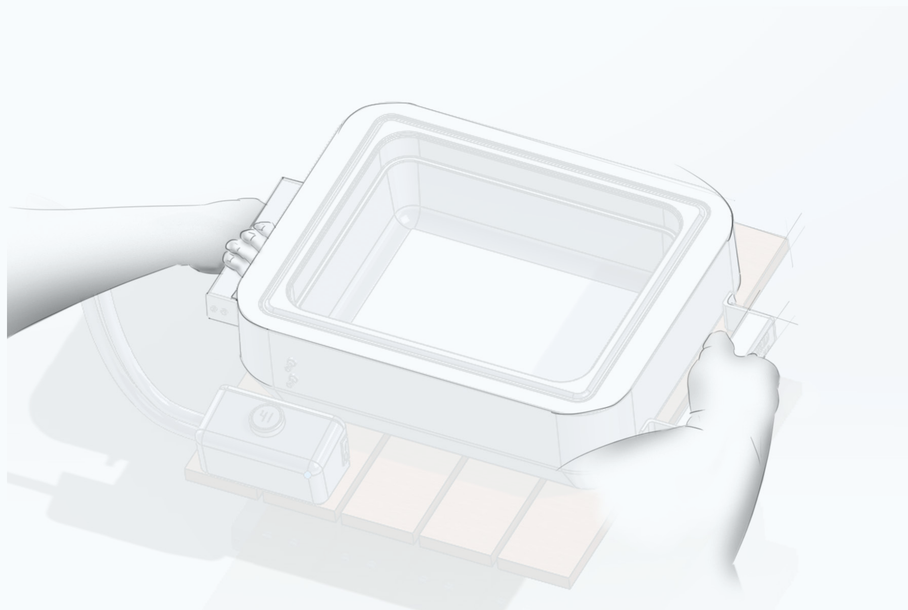
Step 7. Put the food that you want to keep warm from the kamado in the container



Step 8. Place the lid back on the container to keep the food warm



Step 9. If you want to take the container to the table to present the food, first take off the control unit by pressing the release button



Step 10. Now the container is released, take the tray with food and take it where you like. Although no heat is added anymore, the container will stay warm for a while.

Consumer Price Estimation

An estimation of the consumer price of the product is done based on existing comparable products. The estimation could have been done by calculating the price of all separate parts, but since the production methods are not set in stone this would not give an accurate result. Furthermore, the company has good contacts with manufacturers that would be able to give advice if the possibility of production is discussed.

The price estimation is based on adding the price of the Biolite Campstove 2 (159-169 euros) to the price of a chafing dish heated by candles (25-50 euros). This adds up to about 184 to 219 euros.

The Biolite Campstove 2 is used for reference because it contains a custom made heat sink, a peltier element, electronics that are needed to convert the generated energy to the battery, the battery itself, a plastic casing and a metal fireplace, which is comparable to the components that we need. Also, Biolite's revenue is estimated at about 28.4 M per year (Growjo, 2021) which means the amount of products they sell will be in the same order of magnitude to that of 200 Fahrenheit.

Conclusions

Throughout this process, we tried to answer the main research question;

"Is it possible to design a product which proposes a more efficient use of the energy of a kamado barbecue?"

Answering this question, different sub-questions were answered about the viability, feasibility and desirability, tackling the high risk/high rewards assumptions. The potential boundaries of the product have been found, which indicate where the main future challenges of the development of the product lie. In this chapter, the most important requirements are highlighted and a general conclusion will be drawn.

1. Feasibility

The main question for the company was the technical feasibility of the product, which has been answered by multiple experiments and prototypes. The verdict is that the product will work under normal conditions and under most extreme conditions. This will be explained by highlighting crucial requirements and use scenarios.

Heating Capacity

Requirement: The product heats up water from 15 to at least 60 degrees Celsius within 45 minutes when the kamado has an internal temperature of 250 degrees Celsius.

Result: We know that at 260 degrees Celsius, 131 watt of heat can be gathered from the air leaving the topcap. Furthermore, we found that the maximum heat loss lies around 32 watts. Calculating this gives that the product will heat up one litre of water from 15 to 60 degrees Celsius in less than 32 minutes. This means that the user can put in their food in the container after the barbecue has been at this temperature for 30 minutes, which is a realistic timespan.

Requirement: The product keeps one litre of water at at least 60 degrees Celsius when the kamado is at a constant temperature of 100 degrees Celsius.

Result: This is not possible, because we found that too little heat capacity is available from a kamado at 100 degrees Celsius. This means that in certain specific use cases, the au bain marie will stay around 40 to 45 degrees Celsius.

Electric Power Capacity

Requirement: The product produces enough electrical power by its Peltier elements to continuously power the electronics.

Result: The total electrical power consumption of the system lies around 1.23 watts. This means that the system has to produce enough on average to keep the batteries charged. In chapter "findings from the third model" we found that if the kamado is 100 degrees Celsius, the system will produce around 0.25 watt of electrical energy. If the kamado runs around 250 degrees Celsius however, the electrical power rises to around 3.75 watt. Given this data, it is assumed that under most conditions the system should never cause the batteries to run flat.

Working Under Extreme Conditions

Under the extreme condition of using the product continuously at low temperatures, the product will be less functional than required resulting in a lower water temperature or after sustained use, a drained battery. It is expected to seldom occur because in most recipes a quick sear at higher temperatures is required at the end of the cooking session. As soon as the temperatures rises, electrical power production and heating capacity quickly go up and should be able to compensate for the lower energy production in most cases.

Even if the extreme condition occurs, it does not have to be a dealbreaker for the product as long as this is properly communicated to the user. In chapter "Recommendations", advice will be given on how to proceed with user testing, developing prototypes and the product in general.

2. Viability

Comparing it to existing products, the consumer price is estimated at 184 to 219 euros. This might be on the high side compared to a normal au bain marie, but is not exceptional compared to the price of the barbecue itself which is around 1399 to 1499 euros. During the Research and Analysis phase, the persona was found to have enough spending power to expand his or her outdoor kitchen. This is expensive, which makes it realistic that the product is within the price range of the buyer. From the trend research was found that general interest in outdoor cooking will only rise, together with a great range of kamado accessories that are becoming available on the market. This makes it viable to invest in this direction with this innovative product.

3. Desirability

By analysing the current look and feel of the brand, the product has been carefully designed to blend in with the kamado. Although it still has the iconic dark colours and bluntness, it does introduce some slight softer forms to the product which fits to the intended persona and to a brand that has become big and relevant in its field. Furthermore, the usability of the product has been kept as straight forward as possible with the users' needs in mind. Overall, the extensive cultural research shaped the product as it is which makes it likely that it is desirable. However, user research with a working prototype is crucial to truly validate these assumptions.

Impact Of The Product

Overall, the functionality, reliability, usability, user experience and design have been covered and proves that the product is a valuable direction to develop further. Where kamado users were already putting an incredible amount of effort in their dishes, they can finally enhance their dish until the last moment where it is presented to the table in a dignified way and under perfect conditions. The product empowers the user to make use of the normally wasted energy; it is a product which strengthens their outdoor cooking ritual without having to add any additional energy.

Recommendations

Further Development

The first priority in further developing the product should be given to producing a fully functioning prototype of the complete product as proposed. The main reason why the topcap could not be made yet was a lack of resources and time; the topcap must be made out of metal to make it temperature resistant. Although ordering and producing it will take time and resources, as soon as the parts arrive it will take relatively little time to assemble and test. In the meantime, user tests can be conducted with models that represent certain aspects of the product, like mock-ups of the interface or chafing dishes put next to a kamado. For the interface, an experienced electrotechnician should take a look at the electrical circuit to make it function properly and efficiently.
As the prototype has been made and tested, the use cases at which the product does not have enough power can be determined. At this point, it should be determined how many users encounter this problem, and how (or if) the product should communicate the lack of power, and in which way.

From a working prototype, the following questions should be answered and the product should be properly redesigned based on the outcomes.

- Does debris accumulate in the heat recapture assembly? If yes, how does it influence the performance of the product? Can the product be made in such a way that it can be washed easily?
- Can the heat recapture part be optimised and thus made smaller, to decrease the bulkiness of the assembly?
- What will the production costs of the product be?
- Can standard parts be used in the heat recapture assembly, or should these be customized to ensure sufficient performance? How will this influence the price?
- Studying the user; how does the user use the product? Does the user want the product? How big do we estimate the market for this product to be?
- Does the TEG resist the high temperatures it encounters? If not, the maximum air opening of the topcap should be limited such that it cannot exceed this maximum temperature. If the user wants to reach higher temperatures during cooking, the topcap can be taken off to further increase the airflow and temperature, which is already common in the current topcap design.

Advice To The Company

I think the development of this product is very interesting for the company to pursue. As they are longing for innovation, this is a big showpiece of innovation for them and has the potential to address a new professional cooking oriented market share. However, it will cost a serious amount of resources to make it happen. One of the biggest hurdles is their lack of experience with electronics in general. The product has electrical components which need to be prototyped and designed into a Printed Circuit Board. Since they have a big network of manufacturers, it is expected that they can find an expert that is suitable. Even for an electronics expert however, working with Peltier elements is probably new for them, especially to implement in such a product so it should be taken into consideration that it can take months to develop. Also, iterations should be done after the first complete prototype since extensive functionality and user testing must be done, which again takes months of development.

I think the company should take the time to work it out to innovate and to defend their position on the market, the sooner the better. Especially because of the durability of kamado barbecues, which in general tend to last for decades, their focus should be on accessories to let customers keep coming back creating a valid business model for the future. Lastly, they should make sure to further develop their Research and Development team on the field of implementing electronics because this is inevitably going to come across more often in the future.

Reflection

As shown in figure 54, the ideation phase has been shortened to give more space to the prototyping, testing and implementing phase. Also, during the define phase some prior ideation has been done to make this possible. As mentioned before, for the company it was essential to know if implementing this new technology could work. By changing the design cycle this way, it was possible to get closest to a Minimum Viable Product. Working towards a MVP is a modern way of working for many companies nowadays in which all basic functionalities of a product are worked out in such a way that they can be tested and evaluated. And as ProductPlan.com describes it, it allows a team to collect the maximum amount of validated learning about customers with the least amount of effort (ProductPlan, 2021) A version of this method was implemented, with less focus of giving prototypes to users but on the functionality of the system. Many experiments and prototypes gave valuable insights in a relatively short amount of time; it turned out to be an effective approach. Implementing this method made it possible to deliver a clear picture on which aspects of the product are possible, which are plausible and which need further development.

As a personal reflection, I conclude that I should dare to make bolder statements when planning the design process, and look for a better fit between me, the project and the process. I should dare to use alternative approaches if the classical does not fit me. This way I can follow a strong and validated method, rather than force fit the classical design circle on a different mentality. In this project I did bend the approach to my will to some extent. In retrospect however, I could have shortened the emphasize and define phase to give more room to choose a concept earlier. Looking back, building prototypes gave me far more valuable insights than the culture desk research I did.
I am proud on how I have developed myself in gathering new knowledge, on an area that I had very little expertise on. This was achieved by looking into applications in a variety of different products, but also by talking to experts in a variety of fields. I also noticed that the "research by design" approach was very effective, and I will definitely keep applying it during the rest of my career.

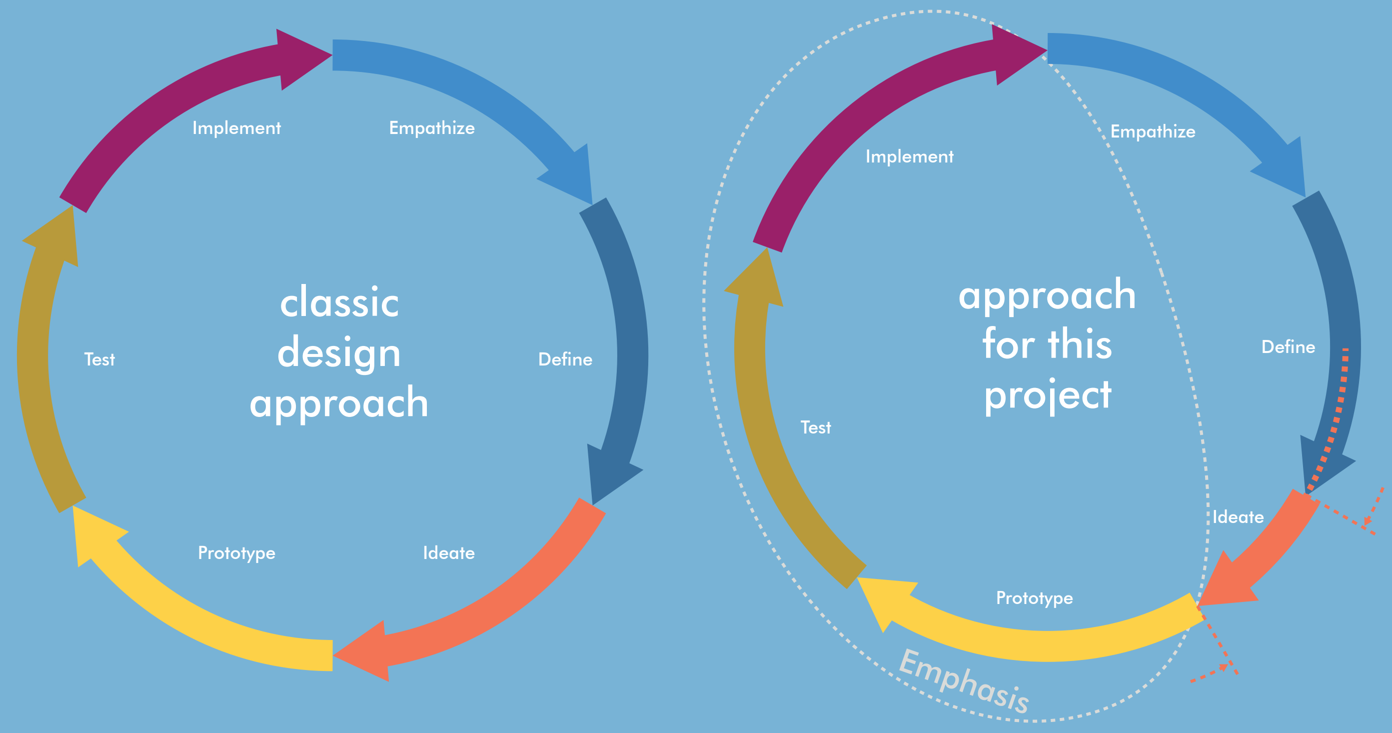
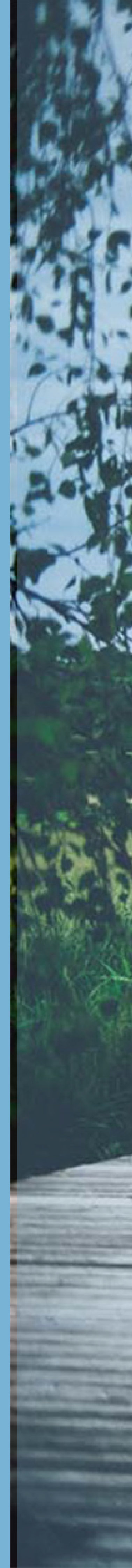


Figure 54. Classic design approach versus approach during this project



I want to thank anybody that has supported me thoughout this project, practically as well as mentally. Special thanks to my family for supporting me and always being there for me.
A special shout out goes to the following people, that have put more time and effort in me or my project than I could have ever asked for, in whichever way they did.

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Chris van Egmond
Djemie Tuankotta
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Derek van der Ploeg
Jessica Overdiep

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Ruud van Heur
Stefan van de Geer
Ad Huisjes

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Bobby Adriaansens
Mark van Hasselt
Omer Wullur

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/APPENDIX - A
Brief History Of The Kamado

A kamado is a barbecue that is based on a ceramic Japanese rice cooker. The kamado in its current form exists for about a hundred years. During the second world war, American soldiers brought it back as souvenirs from Japan, which introduced the kamado to the US. From there, it flew over to Europe as well. However, the origin of cooking in clay pots goes back in time way further, to around 3000 BCE.

Figure 55. a tandoor oven still used today (Dillen, sd)

The Tandoori oven.

The tandoor is in big parts of Asia the favourite oven to bake naan bread and grill meat in. Versions of this oven is found in many cultures as for instance tandyr, tannur and tinur. There are many similarities between these ovens and a kamado and although there is no hard proof, in the book Hete Kolen (Jeroen Hazebroek, 2020) they are sure the tandoori is the mother of the modern kamado as we know it. It uses the same heat conservation principles as a kamado; keeping the warmth captured by enclosing the fire and using insulating materials.

The oldest tandoori was built around 3000 BCE using an oven that was big enough for it to fit in. Baking it was an essential step to make it resistant to high temperatures, just like the kamado today. Since clay was its main ingredient which was easy to find near rivers, the first tandooris have been found near river civilizations: around the Indus and Mesopotamia.

Sumerians, the inhabitants of Mesopotamia, are responsible for the earliest form of written language (History.com, 2017). They wrote detailed records on clay tablets. These tablets were dried or baked, which conserved them to be found back in modern times. Many guides were written down, from harvesting to baking bread. Because of this civilization, the way their dug-in tandoor was used is still known today. Also, the way they made other dishes on smaller pots on the edge of the tandoor is preserved. The influence of the Sumerians influenced cultures all around the Middle-East, and the way a tandoor is used can still be found back.

The tandoori was traditionally used often to bake flat bread. The dough would be stuck to the sides inside the tandoor at a high temperature, as showed in figure 55.

The next evolution

While time, technology and cooking evolved, the next evolution of cooking in ovens leads to Japan. As Kyota Ko states; "If Japanese cuisine was a sphere, rice is its core." (Ko, sd) As the quality of the ceramic pots improved during the Kofun period between 300 and 550 CE, the first kamado evolved inspired by the Yan-steamer. This kamado would be fixated in the house, and would often have a smoke tunnel leading the smoke outside (see figure 57). It would be the centre of the Japanese kitchen, sometimes paired with a Chichirin, which was a smaller fire scale of clay where people would cook or grill on. In the west, it was known as a hibachi, which was seen as the moveable version of the kamado (see figure 56).

Figure 56. Modern Hibach still being sold today (Japanese Korean Ceramic Hibachi BBQ Table grill , sd)

Figure 57. A kamado in a traditional Japanese kitchen. (Juuyoh, 2009)

The Mushi-kamado (Japanese for ricecooker) was the last step towards a kamado. Although it looks about the same as the kamado known today, it was used to prepare rice. This first round cooker was made around the year 1900 near Hekinan, on the Mikawa bay in the Aichi-prefectuur on the south part of the Japanese Honshu island (Jeroen Hazebroek, 2020)

Spreading to the US and Europe

After the second world war, Japan was captured by the US army. One of the soldiers had the idea to use the mushi-kamado as a barbecue. They saw that suddenly they had a barbecue that was capable to cook and steam slowly, but also to grill hot and fast, while the dishes maintained moist. Westerners discovered the cooking capabilities of the Kamado and began flying them back to the U.S. in cargo planes. Not long after, American companies used the growing popularity of Kamados to their benefit and set up shop in order to produce and sell their own lines of Kamado grills. (Jim, 2014) As the market kept on growing in the US, it was a Dutchman that first saw the potential of importing Big Green Egg kamados. In 2001 the first container with Big Green Eggs arrived in the port of Rotterdam ordered by Wessel Buddingh (The history of the Big Green Egg, 2020). In the following years, the kamado has been gaining ground in The Netherlands and the rest of Europe.

/APPENDIX - B
Measuring The Airflow

For the airflow, an experiment was conducted to get a rough estimation of both the difference in temperature between in and outgoing air, and about the volume of air moved per second. Since the kamado is an almost airtight system with a single air inlet and outlet, the air displacement was measured at the damper (air inlet) of the kamado using an anemometer of RS Components, as shown in figure 58. These measurements showed that the kamado displaced between 0.45 and 0.65 litres of air per second. The temperature difference between the air entering and exiting the kamado was measured to be about 249 degrees Celsius, using a Omega RDXL6 SD-USB with multiple type K thermocouple nickel chrome probes.
The following formula was used to calculate the total heat energy.

$$P = \frac{\Delta E}{\Delta t} = Cp * \frac{\Delta T}{\Delta t}$$

Calculating this using the heat capacity properties of air, it gave a heat energy production between 104 and 149 watts. These numbers are relatively far apart because of the measurement uncertainty of the anemometer, but it serves as a good benchmark for the next experiments.

Figure 58. sealing the anemometer to the damper air inlet to measure displaced air.

/APPENDIX - C
Measuring The Heat Output Of A Kamado At 250 °C

Introduction

The main research question to be answered was; how do different heat capturing methods compare in terms of energy output and ease of implementation? This information was crucial before the ideation phase, to define the scope of possibilities. Before the experiment, 3 promising ways of capturing heat energy were chosen. The first was to put a heat conducting solid near the burning area, that would conduct the heat to the outside of the ceramic shell. This was based on the working principle of the Biolite CampStove 2 (bioliteenergy, 2017). The second methods was to capture heat from the ceramic dome. The hypothesis is that the dome insulates the heat relatively well which does not conduct a lot of heat to outside. However, the dome would give a big area to capture the heat from, which could make it suitable anyway. The last method was to capture heat from the air that escapes the top of the dome. The hypothesis is that although air has a low heat capacity, the volume that moves is relatively high. Also, the air heats up significantly, which makes that it carries a significant amount of heat energy. The goal of the experiment was not to get exact numbers, but is to have a test setup that would give an equal comparison and a rough estimation of how they compared. To verify if the test setup was adequate, two technical experts from the faculty Industrial Design were consulted and both agreed to the method. Lastly, this experiment could provide knowledge about to which ideas what heat capturing method would be most applicable.

Method

To get comparable results, water was chosen as a medium to capture the harvested heat. One litre of water was pumped through an aluminium water cooler shown in figure 59. The temperature of the water would be monitored over time during all three experiments. The “Superfish aquarium filter Aqua-Flow 100 zwart 200L/h” was used to pump the water through the aluminium water cooler. The 3 watts of heat energy this produced and dissipated to the water was retracted from all measurements, since a brief experiment showed that these 3 watts effectively all dissipated in the water in the form of heat. A six channel temperature data logger (Omega RDXL6 SD-USB) with multiple type K thermocouple nickel chrome probes was used to measure the water temperature and the temperature around the grill within the kamado throughout the experiments. The water temperature was measured to calculate the captured heat energy over time, to end up with a wattage. The temperature around the grill was measured to make sure the temperature was around 260 degrees Celsius throughout all experiments, to make them comparable. During some experiments, more probes were added to extract more data about the thermodynamics behaviour of the particular experiment. The placement of the probes are specified in 60. During all experiments, the water was properly and equally insulated so heat loss could be neglected.

The following formula was used to estimate the heat energy power of each method;

$$P = \frac{\Delta E}{\Delta t} = Cp * \frac{\Delta T}{\Delta t}$$

Cp is the specific heat capacity of water, which equals 4184 J/((kg*C°)) at 20 C° (Engineering Toolbox, 2021). This means that at every degree Celsius one kilogram of water rises in temperature, the water gains 4184 Joules of heat energy.

Right figure 59: the aluminium water cooler.

figure 60: the container with water, properly insulated with both bubble plastic and aluminium foil.

Setup

Experiment 1: transfer heat through conductive medium
During experiment one, the method of capturing heat through a highly conductive metal medium was tested. The beam is stuck in the kamado, on top of the burning coals. The kamado used is a Grizzly Grill Large, comparable to the kamado used in the other experiments but more suitable for this experiment since it has a standard hole in the base.

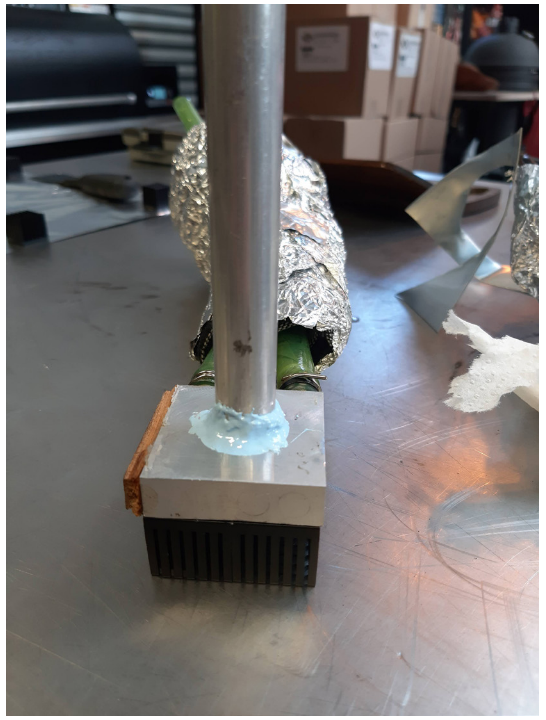


Figure 61. The complete test setup

Figure 62. Aluminium beam glued to the aluminium water cooled plate. The glue used was a highly heat conductive epoxy.

Experiment 2: Heat dissipated through ceramic dome
During experiment two, the aluminium water cooled plate was pressed firmly against the dome, using a strap as seen in figure 63. Between the ceramic shell and the aluminium plate a highly heat conductive heat paste was placed to ensure maximum heat transfer.

Figure 63. Second test setup

Experiment 3: Heat captured from outgoing air
During the third experiment, heat was captured from the air that exits the topcap. A hole was drilled in the cast iron (see figure 64) to create an airflow that was guided past the heat sinks. The heatsinks were glued to the aluminium water cooled plate with highly heat conductive glue.

Figure 64. holes drilled in topcap

Figure 65. heatsink setup placed on top of it

Figure 66. Cardboard windshield placed on top to improve temperature measurement of outgoing air

Results:

Power through aluminium beam: between 25 and 32 watts
Power through ceramic via 40x40mm surface: 14 watts
Power captured from air: 131 watts

In the data can be found that the power of the experiments could decrease over time. This can be explained by the water heating up, which decreases de temperature difference thus slowing the heat energy transfer. That is why the results are measured at the point where the difference between the grill temperature and water temperature are around 245 degrees Celsius, so the power data are comparable.
Another observation was that the ceramic warms up relatively slow, as shown in figure 67. This means that in the first 30 minutes less power will be available, while the air that exits the kamado is heated up significantly quicker. The data of the air test shows that the air temperature just before exit is only 20 degrees cooler than the grill temperature, while the ceramic temperature is stuck at around 100 degrees Celsius below the grill temperature.

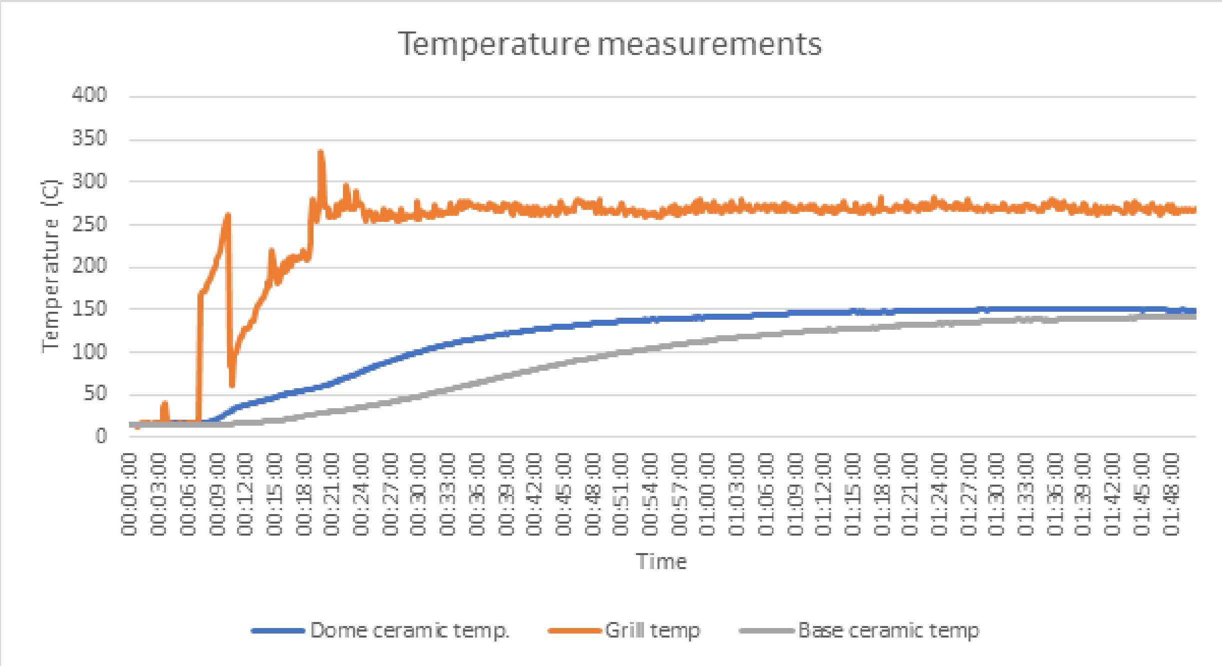


Figure 67. Temperature measurements from the moment the charcoal is lit. The temperature fallback around 11 minutes is the moment the platesetter and heatdeflectors were added. Because they are still cold at the moment they are added, they cause a sudden drop in temperature

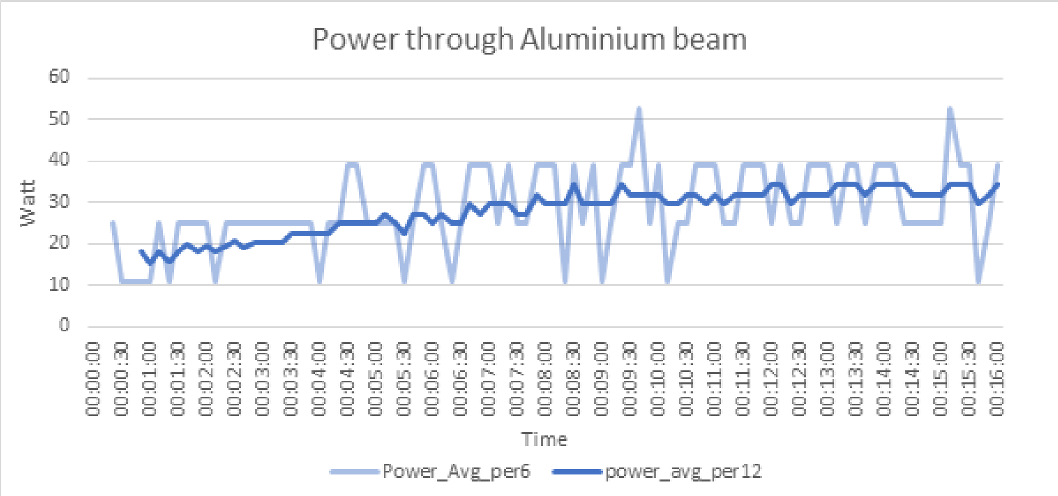


Figure 68. The average power measured from the aluminium beam, calculated over different average sizes to give data that is easier to interpret

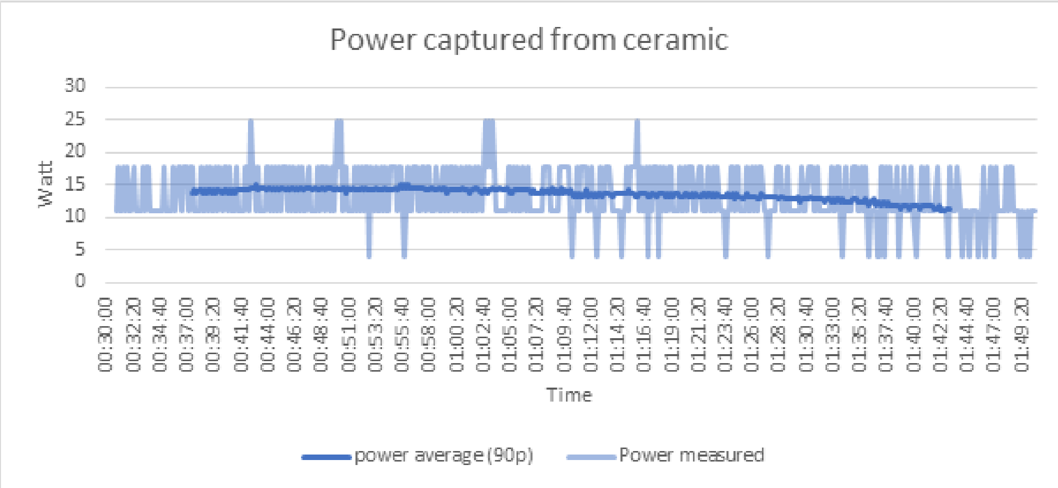


Figure 69. The average power measured from the ceramic shell, calculated over different average sizes

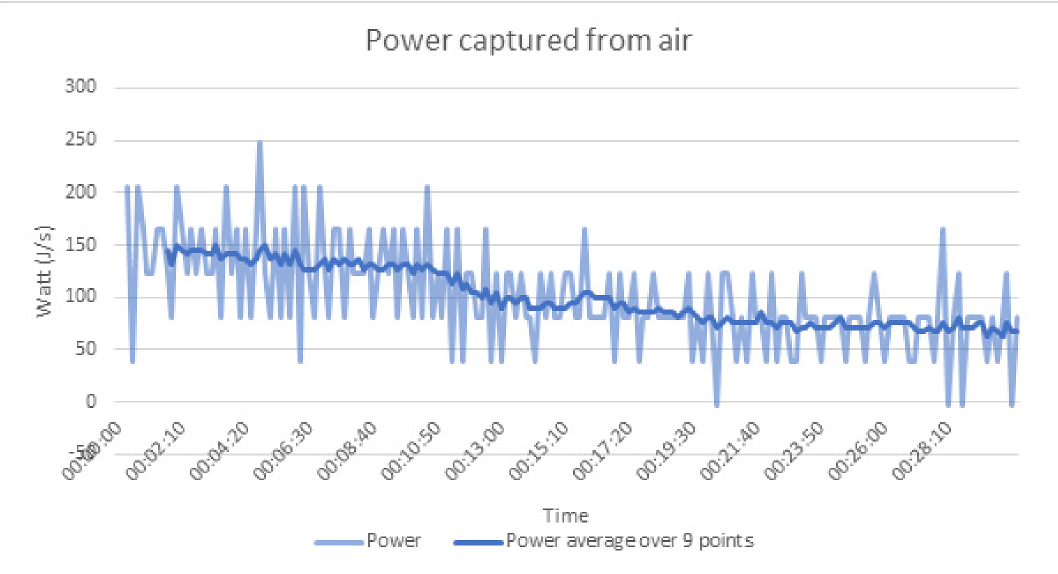


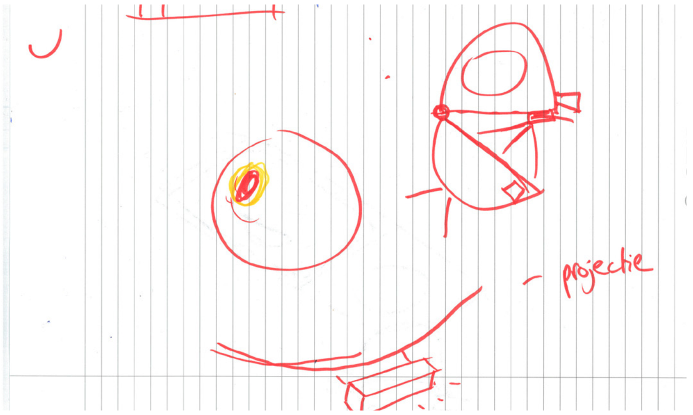
Figure 70. The average power measured from the air, calculated over different average sizes

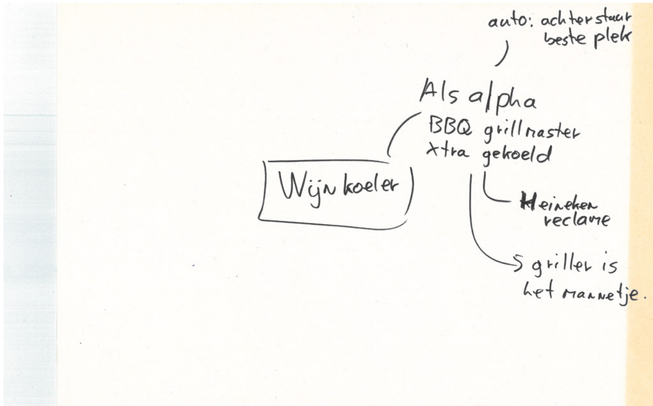
/APPENDIX - D
Initial ideas, brainstorm sessions

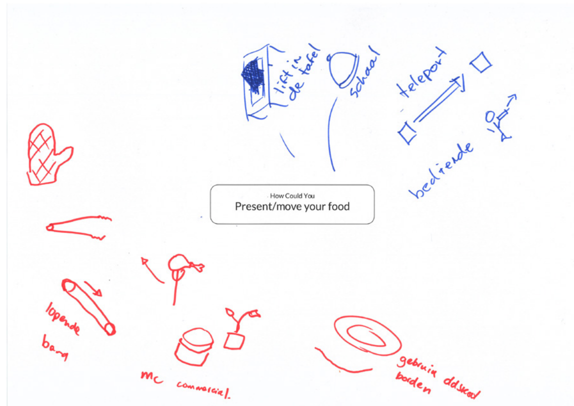
Possible products driven by residual heat or by heat converted to electrical energy.

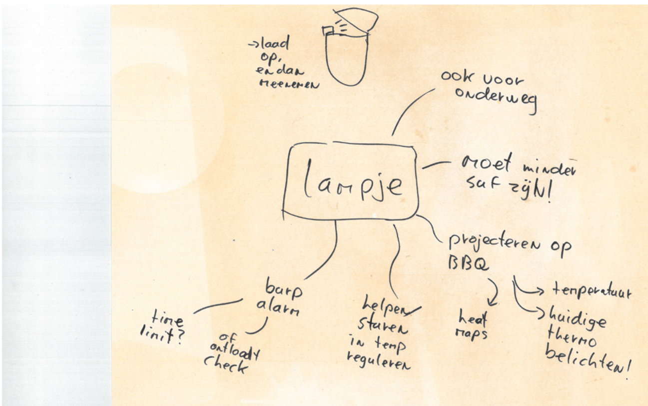
1. Plate that keeps your food warm
    a. *Also for warming up sate sauce*
2. A small LED that aims on the grill
    a. *communicate temperature by projecting,*
    b. *fold away mechanically,*
    c. *present heat maps,*
    d. *Illuminating the standard thermometer*
3. Garden lighting
4. Speaker
5. Wine cooler
    a. *Have alpha position behind the barbecue, as the driver behind the wheel*
6. Something to keep people warm (heating pad)
7. A PID controller, keeping the kamado on temperature automatically
8. An air filter
9. Coolbox
10. Rotisserie
11. Automatic guidance in cooking
    a. *Help regulate temperature*
    b. *Give recipes*
    c. *Give feedback*

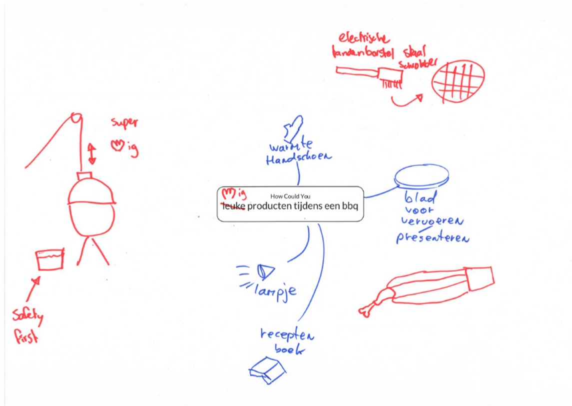
How-to brainstorm sessions

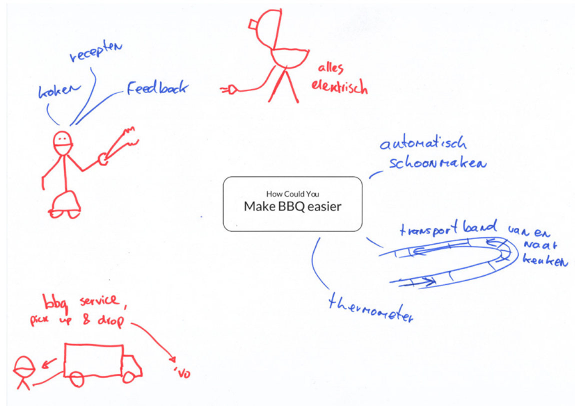


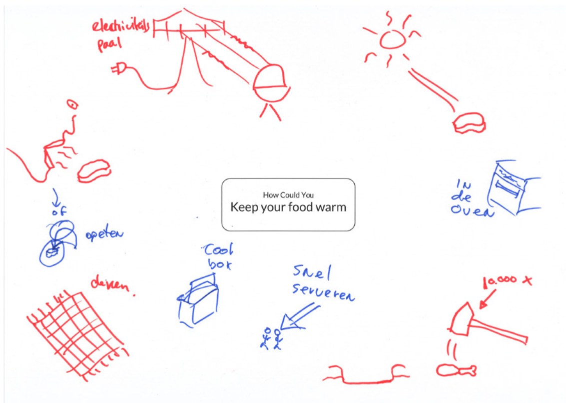


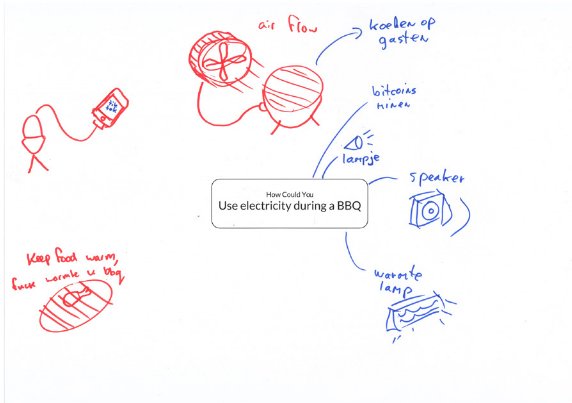


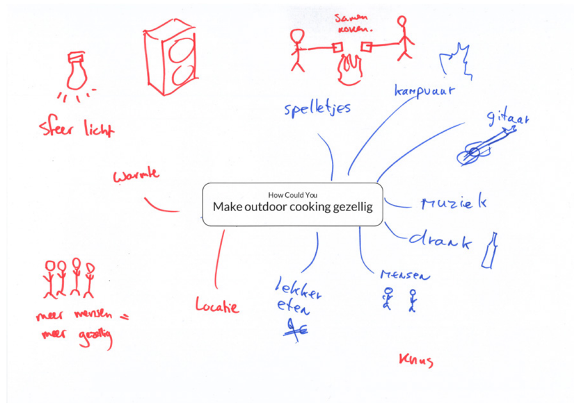












/APPENDIX - E
Interviews Summary

Who is the user of a kamado? To answer this question it was crucial to step away from the company and find users, since it could be that the company did not always know who their user actually was. The interviews were conducted to participants that owned different brands and sizes of kamado barbecues. Luckily, despite the global pandemic and many national restrictions, it was possible to physically see three out of four participants with their kamado. This way, a profound interview was conducted on their outdoor cooking habits, their preferences and their hurdles/frustrations.

Figure 71. Interviewee Rens with his GrillGuru Large kamado.

Main outcomes:

It really depends who you ask to what extend the possibilities of the kamado are being exploited. As one of the participants mentioned; "Most of the time, the kamado is at 180 degrees Celsius." ((Frans, 2021). This is interesting, since one of the main features of a kamado is that the temperature can be regulated so well according to the dish. On the other side of the spectrum, Interviewees Rens and Pim tried to get the most out of their products. Both of the experimented regularly with different dishes, and they both owned multiple thermometers to carefully monitor the temperature of the kamado, as well as the internal temperature of the dish. Most of the participants used the kamado quite often, at least once a month in summer and most of them even a few times during winter. All of them mentioned that the quality of the tools or kamado was important to them. All of them also mentioned that the cooking with fire or the notion of cooking outside was crucial to them, as well as having drinks that go with dinner. Another thing that stood out was the conception that barbecuing and eating meat was a "bad thing". This caused them to either explain it away rigorously (Pim, 2021), or to compensate it in a way, for instance by eating less meat in general (Rens, 2021) or to own a product to (to some extent) compensate it (Pim, 2021). Also, both interviewee Rens and Agniese were experimenting with cooking vegetarian meals regularly.

Frustrations:

The main frustrations that were mentioned multiple times or that stood out were the following;

- Running back and forth to the kitchen can be annoying/a problem.
- Barbecuing when it gets dark is a struggle, some of them use headlights or the light of their phone but both were not considered great solutions
- If you cook for big groups, keeping the food warm was experienced to be a problem.
- Sitting outside until late is a pleasure, but something that keeps you warm other than a fireplace would be nice.

Evaluating with the company

I asked the company what they thought of the personas and the conclusions of the interviews, which gave a few interesting additional conceptions.

- Some participants said that they were sad about the fact that they could not speak to their friends and family that much if they had to take care of the barbecue. When evaluating this with the company, we concluded that it would very much depend on what kind of people are over, since family would probably stay at the table, while a group of friends usually huddle around the barbecue. It also depends on where the barbecue is located relative to the dining table. For the brand Traeger (an automatic pellet barbecue), being able to sit at the table is an unique selling point, so their products might be more focused on families than friends.
- The fact that one interviewee kept the kamado at 180 degrees Celsius was explained by a colleague, since he knew that this is the “safe oven mode”. Generally, people put an oven on this setting since it is a relatively safe temperature. If you then do not know much about cooking on a kamado, it makes sense to fall back on this knowledge.

Interviews salesmen main outcomes

Interview Harlem BBQ salesman (Wouter, 2021)

This shop has quite a status around Harlem, we are seen as authorities on the field of outdoor cooking. Yes, there are different personas that come into my store. For me as a seller, it is especially easy to make a rough distinction between the buyers of different brands.

- Grillguru is in a lower price range, so I notice that these people generally buy less accessories than buyers of the Bastard. Also, I notice that they are well read up on what they want, and they are asking for more information! People want to learn from you, and that is fun. If I do it right, I can built up a relationship with this customer and make them come back for charcoal or new accessories.
- On the other hand, we have the Bastard buyer. A Bastard Large is about 600 euros more expensive than a Grillguru Large (749 eu in this store). To put it baldly, this buyer is easier to fool around with and is easily convinced of buying more stuff. If you make any new product, he will probably be easily convinced to buy it since he has the money anyway.
- Generally speaking, the man buys the kamado but the woman is in charge of the money. I feel like we should focus more on women because as soon as she approves the product, she will also approve to spend the money. For instance, products need to be dishwasher safe, and fit in there. Also a cutting board for instance should fit in a common sink to make it easier to clean, these are things that I think women generally value more.
- People that buy a kamado will notice that they start to cook for more and more people, they will basically invite themselves over. That is why we see people coming back for more tools, a bigger kamado ect. Furthermore, kamado cooking is becoming more professional every day, with people that buy a second kamado, butchers and restaurants that buy one ect. Also the sales of big smokers and pizza ovens are increasing.

Interview with Intratuin salesman (Martin, 2021)

At Intratuin, we have the kamado brands private label, KamadoJoe, Bastard, GrillGuru and one small GreenEgg, but the last one is just to show how ridiculously expensive those are.

- The Bastard is really becoming a big brand name. They only exist for 10 years, started as a B brand but already worked up as a real competitor in the higher end kamado segment. Generally, the buyers of this brand are generally a bit wealthier. People are sensitive to trends, and a black kamado just does it really well at the moment.
- KamadoJoe is not sold that much, but is for the customers that are well read upon kamados since it is such a well-established brand.
- We see that although these barbecues are very much men oriented, women are more involved in the buying process. Although it will never really become a product for women, they are genuinely more interested and generally have a certain veto power, so she needs to be convinced.
- The typical men with beards and tattoos generally don't buy a kamado but rather a smoker or something with more fire. If I look at barbecue forums, I see a very diverse set of people which is a market that is way broader than the "viking looking man".
- The "Dutch" barbecue is losing ground; people are starting to appreciate more expensive meat and longer cooking times. There are lots of American influences here. The more effort that is put in the meat is paying back significantly in a positive barbecue experience.

/APPENDIX - F
Benchmarking Water Pumps

The water pumped around has two functions. Firstly, the water heats up the au bain marie container. The second function is to cool the cool side of the TEG to provide the thermal difference, thus maximizing the power generated. This means that it should keep on pumping, even during little power available. Two pumps were tested, both specified as low energy using water pumps but using a different pumping principle. The first pump was a submersible centrifugal pump, the second one was a diaphragm suction vacuum pump. During testing, the pros and cons of the pumps quickly became clear. The results are shown in figure 72.

Centrifugal pump	Voltage	Amperage	watts	Time(sec)	mL displaced	L/minute	comments
	3.47	0.181	0.628	30	520	1.04	***Minimum voltage for pump to work***
vaccuum pump	1.68	0.064	0.108	60	110	0.11	***Minimum voltage for pump to work***
	2	0.067	0.134	60	145	0.145	
	2.52	0.074	0.186	60	190	0.19	
	3.3	0.084	0.277	60	270	0.27	

Figure 72. Data of the experiment conducted with the two available waterpumps

The centrifugal pump has a higher threshold value before it can overcome the initial static friction and before it starts the water flow. However as soon as it starts the flow, the centrifugal pump displaced twice as much water for the same voltage compared to the vacuum pump.
The vacuum pump however is self-priming, which means that it can start the flow of water by itself without extra power or an additional operation. However as soon as it runs, it only moves half of the water.
If there is enough power available to power the centrifugal pump this would be better, because of the significantly higher waterflow for the amount of energy consumed. Because a battery is used in the system, there should always be enough power stored to overcome the initial static friction. If only little energy flows to the system because the barbecue is operating at low temperatures, the centrifugal pump could also transport water in pulses, which lowers the total energy used but increases the total water transported.
It is important to note that from this data it becomes clear that an extra TEG is needed to provide a high enough voltage for either of the pumps. In figure 73, the grey dotted line shows a possible starting situation of the system, which indicates a voltage of about 1.8 to 1.9 volts. However when the water warms up to 50 degrees Celsius, it drops to 1.3 volts, which is not enough to continuously power either of the pumps tested. To meet the requirements, the pump is required to still transfer heat sufficiently to the au bain marie container.

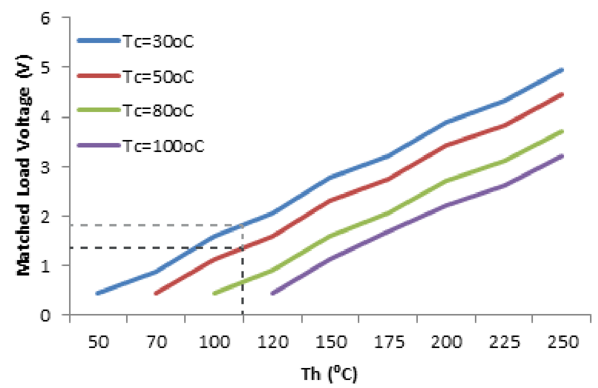


Figure 73. Datasheet of the Peltier element used