MECS-TRIID Project Report

(Public version)

Prototype development of cooker with integrated thermochemical energy storage

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For: DFID and Loughborough University

Date: *February 28th, 2020*

Document Control Sheet

Issue Status	Author(s)	Reviewed By	Loughborough University Approved By	Issue Date
1st draft of final report	Christoffer Bendtsen, Nicklas Bilde	Simon Batchelor		20th January 2020
Final version	Christoffer Bendtsen, Nicklas Bilde	Simon Batchelor	Jane Spencer	6th May 2020

Executive Summary

There is a need for innovative solutions to the challenge of clean cooking, and to enable adoption of renewable energy by households in developing countries. In low-income countries such as Kenya, residents in informal settlements and refugee camps cook using 'dirty' fuels such as kerosene, charcoal and firewood, which causes CO_2-emissions, deforestation by collection of firewood, and bad indoor air climate, which causes the death of 3,000,000 people yearly. Existing solutions show great potential in enabling cooking with clean energy but prices and low affordability of electric battery storage technology are still limiting the wider adoption amongst the world's poorest. Thermochemical energy storage (TCES) shows great potential in solving the stated problems for clean cooking. This report focuses on TCES using salt hydration for storage of solar energy for time-shifted cooking and reaction initiation by hydration using liquid water. Various salts are considered for the application and from evaluation of properties and fit with context, two kinds of salts have been found best fit for utilising in a clean cooking salt hydration application. Through two test iterations with prototype rigs various parameters of both hydration and dehydration have been tested. Results show that salt hydration do have potential as a means of energy storage technology to be used for clean cooking solutions if certain parameters can be optimised. Main conclusions are that the dehydration process is too slow, conversion rates need to be examined, and heat transfer to the pot needs improvement. In this project, proposed solutions include addition of chemical additives, structuring the salt, addition of a heat transfer element and different dehydration measures.

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1 Introduction

1.1 The challenge

In less developed countries in Africa such as Kenya, people in the slums as Kibera and Kirinyaga daily cook over open fires indoors using either firewood, charcoal, kerosene or other ‘dirty’ types of fuels. Many problems exist due to cooking over an open fire, especially using firewood. The collection of firewood and cooking with firewood is the cause of deforestation, soil erosion, respiratory diseases and lastly, premature deaths. The practice of cooking over an open fire is done by nearly half of the world’s population and results in the death of 4,000,000 people every year. It is the only cooking practice in slums, rural villages and refugee camps in Africa.

Challenges with existing solutions

Many existing solutions show great potential in replacing the need to collect firewood. However, there are still some challenges that are difficult to solve with the current solutions’ practices. Gas stoves need fuel, which is either difficult to deliver to remote areas, or too expensive for the most vulnerable to afford in slums. Solar cookers can only be used when the sun is up, and while the requirements of energy for cooking can be addressed with PV and battery storage technology, batteries are still not a sustainable solution to scale and can pose a danger of self-igniting for larger size batteries. Efficient cooking with pellets is another solution, which shows potential in reducing emissions from cooking over an open fire using firewood. These solutions although still use biomass for cooking, and like the gas-stoves need fuel in the form of pellets, which can be difficult to deliver to remote areas. Meanwhile, non-electric solutions have unexploited potential. With phase-change materials, however, the high rate of self-discharge limits the extent of time-shifting and makes it difficult to store energy overnight and cook early in the day.

Thermochemical energy storage

This project will experiment with a new battery utilising salt chemistry for storing energy for cooking, it will seek to drastically improve battery lifetime, it will address the issue about safe handling of batteries as well as safe and clean cooking, and experiment with new approaches to managing energy storage.

Furthermore, this project aims to solve problems related to firewood collection, by providing a clean and affordable alternative to meet the energy demand for cooking, by storing solar energy thermochemically.

The use of renewable energy implies challenges in relation to cooking at certain hours of the day, when e.g. solar power is less effective and also in relation to storing energy overnight for cooking - a challenge that is of high priority to solve.

In short, This project aims to further develop a salt container to be used as a hot plate/cooking appliance for cooking. By injecting water in the salt container an exothermic reaction occurs generating heat for cooking. The wet salt can afterwards be heated up and dried with solar power to restore the chemical energy in the salt, thus charging the battery.

1.2 Aims of the project

The project is designed to operate within a focused demographic, specifically, people living in slum areas in sub-Saharan countries such as Kenya. These are some of the most vulnerable people in the world.

This project will aim to provide a solution by the provision of a clean cooking solution, powered by heat batteries and charged by solar power. By providing a clean cooking solution the practice of cooking over open fires and the collection of firewood and use thereof can be decreased, avoided and hopefully, in future sight, eliminated. The solution proposed in this project is a product-service system where salt batteries for cooking will be introduced with a swapping service, which will require a setup of a swapping and charging station, which could create new job opportunities in operation, allowing people within the slums to generate income. See Figure 1 in *Appendix 01: Figures and Illustrations*.

1.3 Objectives of the project

The objective of the project is twofold and focuses partly on (1) assessing the product/market fit between the technology and the local cooking culture, and partly on (2) further developing the technology to be used in the solution, identifying and analysing the potential of the technology and coming closer to developing a fully functioning product.

The findings from this phase in the development of the solution will provide the basis for building a startup that has the potential to give locals and refugees access to clean cooking around the world and contribute to meeting SDG7.

1.3.1 Assessment of product-market fit

While the project is still in the early phases of the development process, it was of great interest to start validating some of the many assumptions about daily life and challenges related to cooking in a development context. Hence, a market assessment trip to Kenya for preliminary customer validation was conducted in order to gain more insights into the reality of the end-user and to help focus the work on solving a concrete challenge.

The product/market fit was investigated, and partnership opportunities are searched for in the socio-economic and geographical segmentations: rural villages (Kirinyaga) and urban slums (Kibera and Lunga Lunga). In time, the solution could also be rolled out in refugee camps. The focus of the validation study is partly to investigate and validate the feasibility of the distribution model in the context and the fit between the cooking device concept and the local cooking culture.

Criteria for fit between distribution model (swapping system) and local context:

- High population density, for covering more families within an acceptable distance (max. 400 meters distance from home to charging station)
- Users can pay for fuel, for having a starting point for a sustainable business
- Users currently cook with kerosene, charcoal or firewood, for targeting bad fuels and not trying to compete with usability of gas

Research questions for cooking habits:

- Daily cooking routine, for understanding which processes to design for
- Reasons for choosing specific cooking fuel, for identifying key parameters of the solution
- Prices on fuel as well as investigation of how the users stack fuel currently, for knowing what price point to aim for

Lastly, based on the understanding of local daily routines, potential locations for distribution centres e.g. local shops or firewood resellers, and for charging facilities, either land areas or current facilities capable of generating the necessary power are researched.

1.3.2 Technological development

The technological part of the project seeks to gain a deeper understanding of the barriers and opportunities of the technology. The work is split between optimising the discharging process (cooking), and the charging process (storing energy). Based on literature research a prototype is developed and optimised in a second iteration based on test results. The objective is to list requirements for a working application.

The parameters identified to optimise through the development phase are:

- Energy density and required amount of salt (to cook a meal for a family of 4)
- Heat transfer in salt (to be able to transfer the heat efficiently to the food)
- Hydration method and water distribution (to ensure full capacity is reached)
- Material corrosivity (for lifetime and safe handling)
- Time to boil water (to make the solution applicable for cooking beans)
- Time food is kept warm (to estimate heat losses and efficiency)
- Time required for dehydration

2 Methodology

This project approaches the challenge of clean energy for cooking with a low-tech solution, which aims at helping to solve the many environmental, societal and health-related issues from firewood based cooking in sub-Saharan countries.

2.1 Outline of the concept

2.1.1 Thermal energy storage technology

Thermal energy storage (TES) technology is a heavily researched area in various applications from utility-scale to store excess wind and solar power for e.g. stabilising the energy grid to seasonal heat storage for e.g. space heating in homes among other examples. Most recent progress and development within the area are related to energy storage within hot stone and phase change materials as molten salts. Another technology within TES is salt hydration, which provides high theoretical energy density with unlimited storage time. It has not reached its full potential yet, due to challenges regarding low cyclability caused by agglomeration. Salt hydration is a subject within TES that in recent years is being more heavily investigated. Most research within salt hydration looks at hydration using vapour, water in a gaseous phase, as a high energy density and release can be achieved due to the addition of enthalpy of condensation. By hydration of salt, the salt tends to form agglomerates, but some literature suggests that frequent hydration using liquid water can break agglomerates.

The Swedish company SaltX Technology has developed and patented a technology for nano-coating of salts to reduce the effect of agglomeration allowing to repeat the hydration/dehydration cycle more than 50,000 times and is running a pilot project in Berlin in a 10 MWh plant. The nano-coating solves the problem of agglomeration by hydration, but the nano-coated-salt (NCS) do have some requirement for reactions to occur. The NCS has a hydrophobic semi-permeable membrane, which only allows water in a gaseous phase to hydrate the salt. This can be useful in some cases, but also make the product unfit for use in other cases.

The solution developed by SaltX Technology provides a product which is efficient in use within the industrial sector on a more high-level scale, but salt hydration in general still has an unexploited potential within more low-tech solutions, e.g. by hydration using liquid water, if the barriers and challenges of cyclability can be overcome.

2.1.2 Origin of the idea

The project started as a spinout idea from a course at DTU (the Technical University of Denmark) on HardTech Entrepreneurship, now DTU X-Tech. SaltX Technology presented their NCS technology and challenged a team of students to find new application areas. After learning about the challenges of storing energy to be released at high temperatures for cooking, the project was directed towards exploration of the fit between the technology and the needs in the context of cooking in the less developed world.

Initially, the SaltX NCS technology was considered as the material to be used within the solution, but salt hydration, in general, has throughout the research in the project been explored to gain a more comprehensive understanding of what type of material is the best fit for the solution to operate in the setting of cooking in less developed countries.

2.1.3 Proposed solution

The proposed solution is a portable cooking stove with a thermochemical heat battery that is charged using solar power. The storage works by dehydration of wet (hydrous) salt by supplying heat to break down the chemical bonds and boil away water when a given partial pressure is reached. When the salt is charged by heating it up and removing the water molecules, what is left is a dry (anhydrous) salt, which retains the chemical energy stored within the chemical bond. As long as the salt stays dry it remains charged. To release the energy, the salt is recombined with water creating an exothermic chemical reaction which releases the heat that will be used for cooking. See Figure 2 and 3 in *Appendix 01: Figures and Illustrations* for visual representation.

2.2 Gender

For cultural reasons, women and children are often the ones collecting firewood and cooking. Therefore, they are also most exposed to all the negative consequences like spending a huge amount of time preparing food and breathing in toxic fumes. At the same time, men often see cooking as a job for women and are therefore seldom participating in any activity related to cooking.

For a clean cooking solution to be adapted, it, therefore, must be designed for women and children to be able to fully operate it, and the solution cannot rely on the man to take part in any aspect of the process around cooking. An example of this is the maintenance of a stove. Maintenance is typically considered a man's job, but since cooking is considered a job for women, there is a big risk that men will avoid maintaining the stove, which results in a broken stove, and the women cooking on a three-stone fire.

Our goal is to develop a low maintenance stove/cooking appliance, with a distribution model where the stove is leased and swapped regularly. Maintenance will, therefore, be carried out by the distributor and we are not relying on the man in the household to maintain it.

The validation trip to Kenya, furthermore, sought to gain an understanding of how women, men and children are seeing the practice of cooking and how we can design the solution to meet this.

2.3 Intellectual Property Rights

Initially, SaltX Technology's nano-coated salt was considered to be utilised in the solution. The patented technology of SaltX has later been ruled out due to implications of use in low-tech solutions, due to the conditions in hydration of the salt, requiring steam/vapour as a reactant to release the energy stored in the salt.

Pivoting and approaching the problem from scratch by using untreated salt instead of NCS a variety of salt can be chosen from. In order to be fit with the case of clean cooking, two parameters have been set for salt material to be applicable: (1) can be hydrated using liquid water, (2) reaction provides heat of >150 °C. All other parameters can be optimised through testing.

By having a regular salt without any treatment or additives, of course, many problems arise, which has been solved by SaltX Technology. But, when approaching a smaller low-tech application area of clean cooking in developing countries by the same means of solutions, salt hydration, repeatability (cycle stability) is not of first priority to be optimised fully, as it is not a critical parameter as it is in industrial purposes.

Instead, salt hydration using non nano-coated salt has been investigated. Currently, no intellectual property rights exist in utilisation of salt hydration for clean cooking solutions, but with further progress in the design of the solution utilising the salt in a new context, opportunities for claiming intellectual property rights can occur, why some conditions, properties, design suggestions will be held confidential.

2.4 Assumptions made

In the development of the solution in the project, some rough assumptions and estimations have been made.

- The energy needed to boil 8 litres of water is equal to the power required for cooking one meal for a regular-sized family. This amount has also been chosen to be comparable with competing solutions providing the same energy.
- The solution will require no maintenance by the user, as maintenance will be performed by skilled personnel under safe handling.
- Swapping stations will be set-up in centralised areas or integrated in local vendors and the user will transport the solution by foot.
- Water quality for hydration has no influence on the hydration process and any potential degradation will be negligible.
- Temperature and time have been kept steady for charging. It is assumed that an even temperature over time can be achieved from either PV or CSP.
- Rough estimations on heat transfer and convection have been calculated with.

3 Implementation

Due to the broad focus of the project and a pivot in the technological development process, going from NCS to regular salt, this section has been divided into four parts: *3.1 Market assessment and customer validation, 3.2 Technology development with NCS, 3.3 Technology development: Preliminary testing with pure salt, 3.4 Technology development: 1st generation prototype, 3.5 Technology development: 2nd generation prototype.*

3.1 Market assessment and customer validation

3.1.1 The work conducted

During the field trip to Kenya, the criteria for product-market fit was assessed and the research questions about local cooking culture from (1.3.1) were investigated. The data was collected by observation and by interviewing local residents, shop owners, cooks, and resellers of firewood and charcoal, in Kirinyaga, Kibera and Lunga Lunga. Pictures of various observations from the field study can be seen in Figure 4 in *Appendix 01: Figures and Illustrations*. The findings in combination from data from different interviews and desk research has been used to decide on requirements for the solution.

3.1.2 Project findings

Assessment of distribution model fit with local context

Rural villages do not seem to be the ideal market for the first roll-out. The houses in Kirinyaga region are too spread out, which means that a charging station would not be able to cover enough families within a realistic walking distance. Also, most families are self-sustaining with firewood from trees surrounding their property. They cut off the branches and leave the naked stems. Before the firewood is used up, new branches have grown out. However, in the report *2019 Kenya Population and Housing Census: Volume I*, it is stated that the population density is much higher in the south-west regions. Each family will not have as much land and therefore not as many trees to burn, and there could still be a need for the proposed solution in the villages in this area.

Urban slums look like a better fit. The population density is much higher (estimated at 300,000 inhabitants per km^2), and with a maximum walking distance of 400 meters, this will potentially be able to reach 30,000 families. Since the inhabitants do not have access to free fuel, they pay for kerosene, charcoal and firewood. They are moving around a lot, i.e. to get to a public toilet or to buy water and fuel on a daily basis. Very few residents cook with gas, but use mainly kerosene in their houses, and charcoal or firewood on the streets.

Another opportunity is the low-income neighbourhoods, where people live if they managed to move away from the slum. These are often large apartment buildings with middle to high population density. Here, inhabitants use gas because the landlords do not allow the use of charcoal and firewood. Thus, there might still be a market for a cheaper alternative, but substituting gas has less impact on health and environment, and this market is therefore not the first priority.

Solution fit with cooking habits

Fuel stacking is very common. All interviewees owned a lot of different cooking appliances, and the choice of fuel depended heavily on the type of food being cooked.

Most buy beans from street 'hotels', where entrepreneurial women cook big portions of beans or chapati (maize pancakes) during the day. They bring it home and cook it briefly with a few vegetables. The cost of a portion of beans is likely to be lower if they cooked the beans themselves, but it is not possible to fit a 4-hour cooking process into the daily schedule besides working and taking care of the household.

Affordability is key. In the homes most women use kerosene. The fire hazard of firewood and charcoal makes it too dangerous to cook indoors and kerosene is slow compared to firewood, charcoal and gas. Additionally, most are well-aware of the health implications but still opt for kerosene due to the purchase price, despite the fact that the monthly cost of kerosene is much higher than the one of gas. When buying a cylinder of gas, the smallest is 6 kg, which costs 2,300 KSH for the container and 900 KSH for the gas. From the interviewees, this will last for 1-2 months, depending on the usage. A bottle of kerosene costs 200 KSH and will allow the user to cook two dinner meals. The monthly cost of kerosene is then 3,000 KSH. The locals know this but are simply not able to invest the required amount in a gas cylinder. Thus, according to our experience, the ability to buy small amounts of kerosene ends up being the decisive factor for the choice fuel for the vast majority of households in the slum areas.

One could think that entrepreneurial women cooking beans in the streets would be able to afford the investment in a gas cylinder, but here the food is almost always cooked on firewood or charcoal. The reason for this is the large amount of energy needed to boil the beans. Gas is simply too expensive, and the boiling process does not require temperature control.

Conclusion: The solution should target the urban slums, and aim to develop a bean cooker that requires little to no initial investment, and let customers pay for fuel per day, with a daily cost below 100 KSH. It should have no flames and fire hazards and should allow the user/customer to start the bean cooking process in the morning before leaving for work, without being worried about starting a fire.

Identification of local partners and locations for distribution centres

Kibera Town Center (Human needs project) is an obvious collaboration partner, and might also be an excellent fit for a pilot-project and first roll-out. It has a central location, where people from all over Kibera come to shower, do laundry, eat, buy water, and follow courses. They have installed batteries and 35 kW solar panels installed on the roof, of which 10-15 kW is always in excess, and could be used to drive the charging station of the salt batteries. They have deep knowledge about the local environment, and when presented with the solution concept, they expressed great interest in partnership collaboration. Pictures from Kibera Town Center can be seen in Figure 5 in *Appendix 01: Figures and Illustrations*.

Lunga Lunga firewood reseller, is where people from the entire slum and the neighbouring slum come to buy firewood several times a week. It is a location that people know and are used to coming by regularly. Letting the firewood reseller operate a charging or swapping station could be a good way of promoting the new solution to the target customer, and ease the transition towards the greener alternative while avoiding tensions from local competition.

The Community Cooker is a Kenyan NGO, who have built several waste incineration plants in the slums surrounding Nairobi. The heat from the clean incineration is used for cooking, but they are facing challenges with resistance to cooking in public. This could be solved by using the heat to charge the salt batteries, and let customers cook at home. The NGO is interested in further discussions about a collaboration upon technology maturation.

Pictures from observation in Lunga Lunga can be seen in Figure 6 in *Appendix 01: Figures and Illustrations.*

3.2 Technology development with NCS

3.2.1 The work conducted

Research investigating the challenges, limitations, opportunities and potentials from the salt hydration technology provided by SaltX Technology.

3.2.2 Project findings

Difficulty using NCS due steam needed for hydration

- New insight of requirement of steam/vapour for hydration of NCS. The semipermeable membrane only allows water in a gaseous phase to penetrate and start hydration.
- An extension of research was performed to find new salt materials.

Extra energy needed

- By hydrating using steam more energy output can be achieved due to enthalpy of evaporation from condensation.
- More energy is needed to generate steam for hydration.
    - To boil 8 Litres of water, 900g of steam is needed, meaning a total of 1.3kWh of energy where half relates to generation of steam in ambient atmosphere.

Heat exchanger design

- Salt layers can only be 10 mm thick in order for steam to react with it.
- Different designs have been assessed to solve the challenge of packing salt.
- Packing of salt (to boil 8 litres of water) can be achieved in a Ø24cm H13cm cylinder.

Heat transfer in different materials

- Charging/dehydration requires salt to be heated up at high temperatures.
- Aluminium might not be applicable due to the operation temperature, at which aluminium loses nearly all its strength, copper can be used either, as it is a scarce and expensive material. This leaves stainless steel as a safe choice under the circumstances, but this has poor heat conductivity in comparison.

Corrosivity of materials

- Various metals, salt and water in the same structure lead to galvanic corrosion.

PV or CSP for charging

- PV might be a better solution for charging due to controllability and ability to charge even on cloudy days.

Dimensioning of the salt

- A modular single family meal size heat battery is pursued due to difficulty and inefficiency heating the product and surroundings

Control of heat

- Assumption on varying hydration amounts to control temperature has been denied.

Subconclusion

With the findings about the need for steam, the complexity and cost have increased while the versatility has decreased

Thus, the aspect challenge of cyclability has been reconsidered utilising salts without nano-coating. Does the cyclability of CS outweigh the costs of needing steam? The cyclability issue will be investigated and assessed through experiments to see if an accepted cyclability can be achieved by other means. The main intervention from findings during this phase is the changing of salt material to a pure salt in a more simplified approach, where it can be hydrated using liquid water at ambient temperature and pressure.

3.3 Technology development: Preliminary testing with pure salt

3.3.1 The work conducted

Before building the first prototype, a literature study and several preliminary experiments with salt hydration and dehydration have been conducted in order to determine values, conditions and requirements for the design.

In thorough research, various types of salt have been investigated in order to identify which types of salt could be applicable in a solution targeting clean cooking in developing countries. Two criteria were put up for choosing the salt: (1) can be hydrated using liquid water, (2) reaction provides heat of >150°C. From this, a regular salt seems to be one of the best fits, and this was tested from various sources with different grades.

In experiments, individual parameters have been tested, and their influence has been assessed. The hydration process has been researched by mixing water and salt in beakers, and the dehydration process has been simulated by heating small samples of salt in an oven, and weighing the mass difference. See Figure 7 in *Appendix 01: Figures and Illustrations*.

The following sections describing the development process are divided into two subsections: *Hydration* and *Dehydration*.

3.3.2 Project findings

Hydration

- Source of salt material matters. Chemical grade reacts very aggressively. Chemical grade powder releases little power and turns into clay-like texture, possibly due to dissolution in water. Another technicalechnical grade salt reacts slowly and is a fine powder after hydration.
- Approximately 30% of the applied water evaporates during hydration which results in a substantial energy loss.
- Uneven heat distribution caused by very low thermal conductivity of the salt.
- The technical grade source salt has an expansion coefficient of 200% during the first hydration. However, in the later cycles, the density is almost constant.

Dehydration

- Salt can be fully dehydrated in an oven.
- It seems as if the salt dehydrates most efficiently at high temperatures.
- In small samples (30 g), 92% of the hydrous salt, can be converted to anhydrous saltafter 2 hours (conversion is based on the difference of weight of substance before and after time in the oven, this mass loss is assumed to be only water from the reaction).

Hypotheses

An overview of hypotheses and potential measures for improvements can be found in Appendix 02 Hypothesis, Ideas, and Tests.

3.4 Technology development: 1st generation prototype

Optimising parameters for energy storage

3.4.1 The work conducted

Based on calculations and the findings from the preliminary testing, the theoretical ratio between water to boil and salt to hydrate has been calculated, and a scaled-down test setup to simulate the cooking process has been built. *Boiling tests* (BT), where 200mL of water is heated with the heat from the hydration of 300g salt, have been conducted to examine the efficiency of the heat usage. The ratio between salt and water to be ‘boiled’ has been set from the theoretical calculations of how much energy should be released from the reaction plus a safety margin. This is in order to estimate the amount of energy that is released in practice, by measuring the rise in temperature of the water. If the water is brought to a simmer, we can not estimate how much energy is put into the enthalpy of evaporation. The test setup consists of two stackable stainless steel containers, which hold salt and water respectively. First, water is poured over the salt in the bottom container, and then the second container with water is placed on top of the salt. At last, the two containers are placed in a wooden box lined with stone wool insulation. An illustration of the setup and a graph of results from the boiling tests can be seen in Figure 8 and 9, respectively, in *Appendix 01: Figures and Illustrations.*

For dehydration, *Charging tests* (CT) are conducted where 400g of the salt is heated in an oven and the mass difference is measured, to determine the amount of water removed from the salt.

3.4.2 Project findings

Hydration

- According to the calculations, 0.7 kg of salt is needed to bring 1 liter of water to boil, when disregarding heat losses.
- In our experiments, we added an excess amount of water in order to better calculate efficiency from rise in temperature before boiling. We reach a maximum of 44.5% energy transfer efficiency, meaning the theoretical application energy from the reaction which is transferred to the water.
- After 4 hours, the water temperature is around 10 °C larger than surrounding temperature for all experiments.
- Ideas for increasing efficiency are to increase heat conductivity in salt and to improve the insulation of the cooking device.
- The method for hydrating the water is of big influence on the total amount of energy released by the reaction. Emphasis must be put on developing a technique for injecting water with even distribution after complete assembly.

Dehydration

- Time required to dehydrate the hydrous salt greatly increases by scaling up the sample size by a factor of 10 to 400g, which emphasizes the need for improved thermal conductivity, and ability for vapour to escape from the powder and a solution to remove vapor from the air in the oven.
- After 6 hours in an oven with the large scale salt at high temperature, 92% of the water was removed

Hypotheses

An overview of hypotheses and potential measures for improvements can be found in Appendix 02: Hypothesis, Ideas, and Tests.

3.5 Technology development: 2nd generation prototype

Optimising parameters for regular salt

3.5.1 The work conducted

A second generation prototype has been developed and built, based on the findings from the previous experiments. The salt container is a stainless steel box with a water injection pipe with small holes mounted in the bottom. The water container fits into the salt container, and ensures good physical contact between salt and water container and closes the opening of the salt container. The hydration process can now be initiated after complete assembly of the cooking setup.

With the attempt of improving the thermal conductivity of the salt and allowing vapour to better escape the salt, hydration and dehydration experiments have been conducted with a range of materials added to the salt: sepiolite, stainless steel balls, a stainless steel sponge formed to have similar volume as salt and fit in the salt container, and a ‘heat sink’ made from copper foil folded into fins.

Dehydration experiments have been carried out by placing a stainless steel container with 400g hydrous salt in an oven at high temperatures, with 100 °C in difference between experiments, and an external fan blowing air through the oven to ensure continuous ventilation. Again, experiments with the different additive materials have been conducted and afterwards, the mass difference is measured, to determine the amount of water removed from the salt. Pictures from the testing with the prototype can be seen in Figure 10 and graphs of results from hydration and dehydration tests in Figure 11 and 12 in *Appendix 01: Figures and Illustrations*.

3.5.2 Project findings

Hydration

- The boiling tests with the 2nd generation prototype showed improvement in all boiling tests compared to the results from experiments with the 1st prototype. After 4 hours, the temperature is close to 50 °C for all tests.
- The highest temperature reached was 92 °C during BT6. The salt used for this test was a technical grade salt which had already been hydrated and charged in the oven. While the charging step still takes too long, it does work for storing energy. No additives were used in this experiment.
- No additive materials have shown improvements in the boiling tests.
- In BT8, the improved insulation with EPS shell showed slightly better heat retention, but still, much heat is lost.
- In BT10, the time needed to get to maximum temperature was shortened significantly.
- In BT11, the added copper ‘heat sink’ showed better heat transfer over time to the water container from the salt. The duration of getting to maximum temperature was also shortened significantly, but not compared to BT10.

Dehydration

- Adding sepiolite showed no improvement in heating rate, and after 3:30 hours, only 49% of the water was removed.
- Conducting the dehydration test circulating the air after 4 hours in the oven at high temperatures only 48.16% of the bonded water was removed. This is significantly less than the without circulation, where 92% was removed. We suspect that the air flow from outside has cooled down the salt container locally on one side. Thus, the low conversion rate could be the result of a significant temperature gradient across the salt bed.
- Adding stainless steel balls showed no improvement in heating rate, and after 8 hours 81% of the water was removed.
- Adding a stainless steel sponge showed some improvement in heating rate and after 8 hours, 96.4% of the water was removed.
- In most cases, the temperature drops/stalls after reaching 100 °C, due to evaporation of excess water, not bound by the salt. This is a sign of overhydration or uneven distribution of the water, and it slows down the charging process.
- Additionally, after reaching 100 degrees below oven temperature, the temperature drops/stalls in the salt. This is likely to be caused by the water being released from

the salt, and then evaporating. For CT4, the temperature starts rising again after 5:30 hours, which could indicate the point where most of the water has evaporated. For CT5, this point was already after 2:30 hours, indicating that the steel sponge helped speed up the evaporation.

- In CT7 where temperature was raised by 100 °C, the temperature stalls at a higher temperature at 30 °C higher than previous experiments, and starts to rise already 30 minutes after this temperature was reached. Although, from measuring the container after 4 hours in the oven, still only 81.6% of the water was removed. This indicates that temperature definitely has an effect, but still heat transfer in the salt is of high importance.
- Due to the simple nature of the chemical reaction, a proportionality between the amount of reacting salt and the heat enthalpy released from the reaction is expected. However, as the fraction of unreactive matter increases, the amount of energy needed to heat up this matter also increases, why there might be a slightly bigger negative effect on the energy density than the relative reduction in conversion rate.

Hypotheses

An overview of hypotheses and potential measures for improvements can be found in Appendix 02: Hypothesis, Ideas, and Tests.

3.6 Limitations of the innovation/approach/design/system

3.6.1 Distribution model

Introducing a service system, where users pay to exchange batteries at a central location on a daily basis, requires some conditions to be fulfilled before the intervention would gain acceptance. In rural villages, the houses might be too spread out, which means the user will have to walk too far everyday for the service to be attractive. Also, there is a great challenge in competing with firewood from their gardens.

We are still yet to fully understand the rate of the decomposition of the salt. If severe, the logistics of the solution is more comprehensive and industrial furnaces are needed to recover the original salt at higher temperatures, and occasional transport of the batteries between rural and industrial areas could challenge the overall cost of the system. However, slums could be ideal segments for a first roll-out.

3.6.2 Technology development

The technology still requires a decent amount of work and development, before getting ready for market roll-out. The efficiency of the boiling process needs significant improvement, and the charging time needs to be reduced considerably. Once this is solved, the product needs to be designed for safe handling, making sure the user does not have physical contact with the corrosive salt, and does not breathe in the fumes. This should be solvable through thoughtful design.

At this point, temperature control is still not possible, which makes it difficult to see a use case of frying with the cooking device. Instead, it resembles a hay-box, and the food to be cooked will have to be boiled.

The cyclability of the charging/discharging processes is lower than expected, since it is not possible to use NCS, but this can be solved logistically by heating the salt up to a higher temperature at another location where this is possible. This extra logistic loop will inevitably add costs to the service. But, from research natural salts in salt hydration have an anticipated cyclability of up to 50 cycles, which means that frequent regeneration might not be a deal-breaker.

4 Practical applications to the national cooking energy system

The low-tech cooking and charging solution combined with the sharing economy approach allows for a low barrier of entry, both regarding the economy, usability and logistics. The solution reduces emissions and mitigates deforestation, enables more women and children to go to school and/or frees up time for income-generating activities. As the stoves must be charged and then exchanged for uncharged stoves, the technology requires skilled personnel to take care of the daily operation.

4.1 Off-grid solution – Infrastructure on foot

With an ‘off-grid’ solution where the energy is distributed by foot, the installation is both simple, cost-efficient and quick since no physical infrastructure such as electricity grids are needed. This overcomes the resistance towards implementing permanent infrastructure, in especially refugee camps, and the system could be moved somewhere else, in case a camp is being closed down.

4.2 Charging of the battery

Based on our findings in the project, the product, when rolled out in the setting of e.g. the slum of Kibera, will need some sort of infrastructure built around it. The heat batteries will be charged centrally at charging stations using either PV or CSP. As the population density is quite high in slums the average distance to charging stations will be short and charging stations can create jobs for people in the slums. At charging stations, personnel are educated in safe handling of the batteries. Once charged, the batteries are stored, until a user exchanges an uncharged battery, and can be initiated by the adding of water through e.g. a valve by the user.

4.3 Acquiring the ServedOnSalt Cooker

The ServedOnSalt Cooker will be put for the users disposal once the service has been bought along with a small deposit. The user will receive a charged battery to bring home and cook with for 0.5 GBP per swap, which is a price point estimated from the price of other fuels available and what some of the most vulnerable can afford per day.

4.4 Time until Return of Investment

Even with very low estimation on what the swap fee should be in order for the most vulnerable to afford and to be competitive as a fuel substitute to currently used fuels in the normal cooking practice. A small profit margin of 0.11 GBP per swap is assumed, meaning that a pilot project with 10 families would generate a maximum profit of 3.34 GBP daily. The finance for the development of prototypes able to test and use in a pilot project in Kibera are still just estimations since many challenges need to be solved before the true production cost can be calculated. Although, the estimations are believed to be realistic and a return of investment for such a pilot project will be 20 months when working with minimal margins.

5 Next steps

5.1 Step 1: Further development of technology

The next steps after the end of this project will be to further develop the prototype with insights gained from the continuation of the lab testing towards a functional prototype that can cook beans, and that we are confident to let end-users test. This will enable us to validate the business and distribution model, and assess the willingness to pay for our solution. Only after such validation tests have been conducted will we be ready for production and first pilot project.

To further develop the prototype and technology, we will build test rig setups in order to find explanations for the hypotheses formulated in the *Appendix 02: Hypotheses, Ideas, and Tests,* here are included ideas for improvement and plans for testing.

The further development of the technology will seek to optimise the critical processes which we have obtained a better understanding of in this project:

Processes to optimise

1. *Reduce dehydration time*
2. *Increase efficiency of heating water*
3. *Increase conversion / Reduce rate of agglomeration*
4. *Increase efficiency of cooking beans*

Subprocesses to optimise

- Reduce dehydration temperature
- Increase energy density
- Increase thermal conductivity in salt
- Reduce expansion rate
- Increase reactivity

The optimisation process will be attacking the problem with an approach similar to the one of SaltX, but will only continue until we have a prototype that is able to meet the targets below:

Targets

1. *Dehydrate 400 gram of salt by 90% in 30 minutes*
2. *Bring 2 litres of water to boil with 2 kilogram of salt.*
3. *Run 20 cycles with conversion rates above 80%.*
4. *Cook 500 gram of beans using 2 kilogram of salt*

Once these targets are achieved, we will continue the work towards building a prototype that can safely be tested by a customer in a local context. For that, a closed container design needs to be developed in order to ensure safe handling of the salt.

5.1.1 Cost, time and resources

- The prolonged development phase of a functional prototype is estimated to have a duration of 6 to 12 months, and we are hopeful that within 6 months, we can have some promising results ready to in the next 6 months start developing a user-ready prototype and test this.
- Two persons working full time (writing master thesis) on development with regular back-and-forth discussion with relevant people, chemists, researchers, mentors etc.
- More equipment and facilities are available now meaning cost will be in relation to the materials and resources needed to conduct the tests. Approx 5,000 GBP. Further costs can occur if new equipment is needed to conduct tests.

5.2 Step 2: Pilot project with functional prototypes

Once a functioning prototype has been built, the next phase will be a validation/feasibility study in a small 'pilot project' with 10 prototypes in the Kibera Town Center. Here the solution will be tested both in the hands of the user under realistic circumstances.

5.2.1 Cost, time and resources

- The validation/feasibility project will have a duration of approximately a month, but also a month is needed for planning and activation of staff and setup of charging stations.
- More hands are needed for the project to run smoothly and efficiently, also people with cultural and local knowledge. Around five people are needed in total.
- Cost for this pilot would be salary for the people hired in the project, transport expenses, accommodation expenses and also the production of the prototypes. Approx. 10,000 GBP with reservations to unforeseen challenges encountered in the project.

5.2.2 Future funding planning

Specific funding opportunities in the next steps and their focus/requirements:

- DTU Skylab funding, for developing the technology, up to 16,700 GBP.
- Otto Bruuns Fond, for developing prototypes, up to 5,600 GBP.
- Micro Grant Sustainable Development Goals, for working with the SDG in a start-up, up to 5,600 GBP
- DTU Tech Transfer, PoC Grant, to gain proof of concept - up to 57,000 GBP.
- DTU Discovery Grant, to mature technology toward commercialisation 14,000 GBP
- CARE Cooking Challenge
- Access2Innovation, 'Partnership Driven Innovation for the East African Growth Markets' (PIVØ) up to 57,000 GBP.
- The Danish Fund for Innovation, Innobooster, between 10,000-60,000 GBP.
- Climate KIC, Climate LaunchPad, up to 85,000 GBP.

5.2.3 Partnership developments and new engaging actors

- New acquaintances in different chemical engineering departments at DTU; Gerald Englmair (TES and salt hydration) and Susanne Mossin (Sustainable energy).
- Invited to be part of the DTU Skylab incubator where various people can assist us.
- Won the opportunity for a discovery loan from PreSeed Venture.
- Invited to join HelloScience.io enabling collaboration to accelerate SDG impact.

6 Dissemination Plan

The aim of this project is to develop a clean cooking appliance solution, which in the future can be offered as a product service system to slum areas, rural villages and refugee camps. The objective is to gain traction in development and promote knowledge of our work and intention in order to progress and create a launch pad for further development. We intend to communicate our intention and work through various channels:

6.1 Local in Kenya

The solution, once a functional prototype is built, should, initially, be implemented in a ‘pilot project’ in Kibera Town Center. Gatherings in the local town center can be conducted to promote the pilot project and gather insights from the users.

6.2 National in Denmark

Attending various events to talk face to face with potential collaborators and investors, in order to further progress our solution. Joining HelloScience.io to more easily create connections with people with passion about SDG impact development. Showcasing the prototype to contacts within humanitarian sectors of UNHCR and UNEP DTU, to gain publicity.

6.3 International

We have launched a website, which so far has acted as a landing page, but will be updated regularly and aims at promoting our work and case along with progress. Furthermore, additional showcasing of our work through LinkedIn posts and newsletters and papers wanting to write about us.

Additionally, we are considering writing a research paper, as a part of our thesis, about the work we are doing with ServedOnSalt and to illuminate salt hydration from a new angle and provide new insight to the area.

7 Conclusion

Throughout the MECS-TRIID programme, the salt hydration technology for use in application of clean cooking has been tested. Various salts have been considered for the application. During the project, an important finding was that the benefits of nano-coated salt may not weigh up the advantages of high cyclability, as the nano-coated salt only allowed hydration by steam. If good cyclability can be achieved with regular salts, there is a good potential for developing a feasible low-cost solution.

Various parameters have been tested with a chosen salt, in order to map challenges and find possible solutions to mitigate these. In this project, the challenges which are being addressed and the current results are described in *Appendix 02, Hypotheses, Ideas, and Tests*.

In summary, the main challenges addressed, and conclusions from testing are:

The process of charging the salt, dehydration, is still too slow in order to gain a reasonable energy balance between hydration and dehydration.

Dehydration at different temperatures, adding structure with various elements and circulating the atmosphere in the oven are all parameters which have been tested in relation to reducing dehydration duration. Currently, temperature seems to have a high influence, but can potentially also negatively influence the reactivity of some salts. Furthermore, circulation of the atmosphere has an impact on the dehydration rate.

Efficiency of transferring heat from the salt reaction to the water/food container.

It has been proven through various tests that a lot of energy and heat is released when hydrating the salt, but the salt has a very poor heat conductivity, thus, a lot of the generated energy is going to waste. Therefore, solutions for transferring this heat to the water container have been thought out, and some tested in this project. A finned heat sink made out of copper foil had a positive influence of the maximum temperature in a boiling test, and showed a better heat transfer over time as temperature was better retained in the water container. More tests have to be conducted with various designs for heat transfer elements using different materials, as the copper seemed to have reacted with the salt.

Cyclability of the salt is yet to be investigated thoroughly.

This project has not investigated the cyclability of the salt to a satisfactory extent in relation to the intended application. However, the phenomena of agglomeration of the salt has been addressed from testing, and possible solutions to mitigate this problem is to be tested in further work.

A functional closed container design which end-users can safely operate still causes some challenges.

The salt is powdery, at least after one cycle, by nature. Therefore, it is difficult to design a solution for users, as this means the salt must be enclosed, so that the user can not come in contact with the salt, i.e. breathing in the powder. This, however, leads to new problems due to pressure and temperature which again might have an impact on agglomeration of the salt. In this project mainly open systems and semi-open systems have been tested.

The charging system needs more development and detailing.

This project has mostly focused on developing the salt technology to be used within the heat battery. It has addressed the charging process from the technology point of view, by testing dehydration duration. The energy for dehydration can come from various sources, where solar is one, and different concepts of how to dehydrate the salt is still under development.

Using salt hydration for making a low tech heat battery for clean cooking in developing context does seem to have potential if certain parameters can be optimised. This project has proven that the technology of salt hydration can be utilised in a small-scale system. The authors will further be testing the technology and optimising it for the clean cooking application, and are aiming towards developing and building a user-ready prototype.

Appendices

01: Figures and Illustrations [PUBLIC]

02: Hypotheses, Ideas and Tests [PUBLIC]

03: High-Level Requirement Specification