

# **FINAL REPORT**

## **Network Project**

### **Small scale concentrating solar energy system with heat storage**

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## Foreword

This is a final report of the research activities in a Network Project between universities in several African countries and NTNU. The focus area is thermal solar energy: testing of concepts for small scale concentrating solar energy systems with heat storage units. The core project is a NUFU project but other projects have been initiated and coordinated towards the same objectives. This includes a social science project on the social side of adaption to new technology.

The main projects terminate at the end of 2012, some of the PhD periods extend into 2013. This report covers the activities of the extended project.

It has been a pleasure to participate in this Network project, and I am grateful for having had the opportunity to work together with colleagues and graduate students at all the participating universities.

### *Participants*

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30 January 2013  
updated NORGLOBAL project November 2013  
NTNU

# 1 Summary

## Objectives

The main objectives are to develop, construct and test small scale concentrating solar heat collectors with integrated heat storage units. The first application area is for food preparation, and the first target systems are for institutions (schools, hospitals, health centers etc.)

As these are university based activities, the education and collaboration aspects are also important: The project shall stimulate the participating universities to establish laboratories and research groups on applied solar thermal energy.

## Participants

Several projects have been coordinated to give synergies on the technical (NUFU, NRC), social (NORGLOBAL) and educational aspects (NOMA, EnPe) of the work. The participating universities have been

- Norwegian University of Science and Technology, Norway
- Eduardo Mondlane University Mozambique
- Makerere University Uganda
- University of Kwa-Zulu Natal South Africa
- Addis Ababa Institute of Technology Ethiopia
- Ethiopia Institute of Tehnology – Mekelle Ethiopia
- Bahir Dar Institute of Technology Ethiopia

## Tasks

Each university has focused on particular research aspects of the energy system (concentrators, solar trackers, heat absorbers, heat transfer, storage, insulation, computational models, control systems, applications, social aspects). Both latent heat (solar salt) and sensible heat (rock bed, oil storage) have been investigated for heat storage. Air, oil and steam have been tested as heat transfer options as well as direct illumination of the heat storage.

A comparative study on the adaption of solar systems in India and Africa has been made, based on an existing solar system (Scheffler reflector). The social based studies have also included solar cookers and solar photovoltaics.

## Results

Solar energy concept have been demonstrated for:

- Air based dish system with a rock bed heat storage
- Self-circulating oil based trough system with oil or solar salt for heat storage
- Pumped oil system for injera baking applications, including a new ceramic injera pan
- A double reflector system for direct heating of a latent heat storage (heat battery)

The project has resulted in establishment of solar laboratories, and a regional network of solar researchers, both staff and graduates and within both natural science and social science. About 20 master students have been involved in the solar research, some recruited from the parallel NOMA program. 4 PhDs have graduated, 5 more are expected to graduate in 2013.

## 2 Background

Large scale concentrating solar systems can convert solar thermal energy into electrical power. The sun rays are concentrated onto a receiver where the heat is absorbed and transported to a steam generator which drives a turbine connected to a power generator. The objective of the current project is to develop simplified small scale systems which are not intended for power generation, but to meet the thermal energy needs at the level of institutions and households.

The project activities aim at studying prototype small scale systems for collecting and storing heat at high temperatures (about 250 degrees C). The stored heat can then be utilized for a number of purposes. The first area of application is for food preparation where the aim is to replace wood, kerosene or gas with solar powered cooking.

Prof. Em. Jorgen Løvseth initiated research activities in this area through early NUFU projects (Norwegian Program for Development, Research and Education). Based on the previous activities, the NUFU Network project was established for the period 2007-12. Parallel projects have been initiated at NTNU, allowing for construction and testing of solar units also in the laboratories of NTNU and also for inclusion of social science aspects into the project.

The following is a description of the project activities and the main results.



Final meeting (Trondheim)

## 3 Projects

The research activities are financed from several sources.

### **NUFU (The Norwegian Program for Development, Research and Higher Education)**

The NUFU Network Project involves 5 universities in Mozambique, Ethiopia and Uganda (2007-12) together with NTNU. Staff members at the various universities are supported to undertake PhD and MSc studies on different aspects of the concentrating solar system. The work builds on the experience from previous projects, including a collaboration with University of KwaZulu-Natal, Durban.

## **NTNU**

One of our PhDs at NTNU is sponsored by internal NTNU funding

### **Idefondet and Statoil**

We received support from Idefondet at NTNU, together with support from Statoil. This also facilitated a project application to the Norwegian Research Council (NRC).

### **NRC: Renergi program (Norwegian Research Council)**

We have a project under the RENERGI program for the period 2009-2012. One PhD is also supported through a NRC project at the Centre for Renewable Energy (NTNU, SINTEF, IFE).

### **Quota Scheme**

We have been awarded two PhD scholarships and one PhD sandwich scholarship under the quota scheme. This is support at the level of standard Statens Lånekasse rates, combination with other finance sources is often needed.

### **NRC: NORGLOBAL program**

We were awarded a social science PhD under the NORGLOBAL program (2010-12). The PhD task is on the social aspects of implementing solar energy systems. The work involves collaboration with University of KwaZulu-Natal (PhD) and Eduardo Mondlane University (master).

### **EnPe (Energy and Petroleum)**

We took part in the preparation of an EnPe proposal linking NUFU and NOMA (Norads Program for Master Studies) activities in a new MSc program at Mekelle University (Ethiopia, Tanzania, Uganda, Mozambique, Malawi). The project started in 2010 and includes (in combination with the Quota Program) a PhD on concentrating solar energy in our lab (from Mekelle Univ.) and a sandwich student from Mozambique.

## **4 Collaboration**

The project has resulted in a regional network of academics and also of graduated students within solar energy. Long term collaboration is important, and has also lead to joint applications in response to calls on research and education projects in renewable energy.

The link between the social and the technical oriented research tasks has been useful in our project. Development and deployment of a solar energy unit are not the same type of problem, social, cultural and economic aspects may slow down the acceptance of new technology. We aim at testing solar systems at the level of institutions. The experience on adaption of small scale solar cookers, and the comparative study on larger Scheffler systems in India and in Africa are useful when specifying the requirements for new systems.

At NTNU we have also invited students from the local engineering college (HIST) to take their BSc research task within the solar project. Their contributions to constructing and testing of solar tracking methods have been useful.

The NUFU project has had close communication with a NOMA project on master programs on renewable energy. The objectives of the NOMA program is to contribute to establishment of new MSc programs, whereas the NUFU program is more oriented towards capacity building through research projects (mainly PhD).

Our experience has been that the NUFU project and the NOMA program have been mutually beneficial. The NUFU project receive requests from motivated students to take part in solar research and the NOMA program gets support in the form of supervision from the NUFU researchers. NOMA students have been involved in NUFU project activities in Maputo, Mekelle and Makerere. The contact between the programs on the solar research lead to a joint follow-up EnPe project. An illustration of the collaboration is given blow.



Lecturing (Mekelle)



Laboratory visits (Addis)

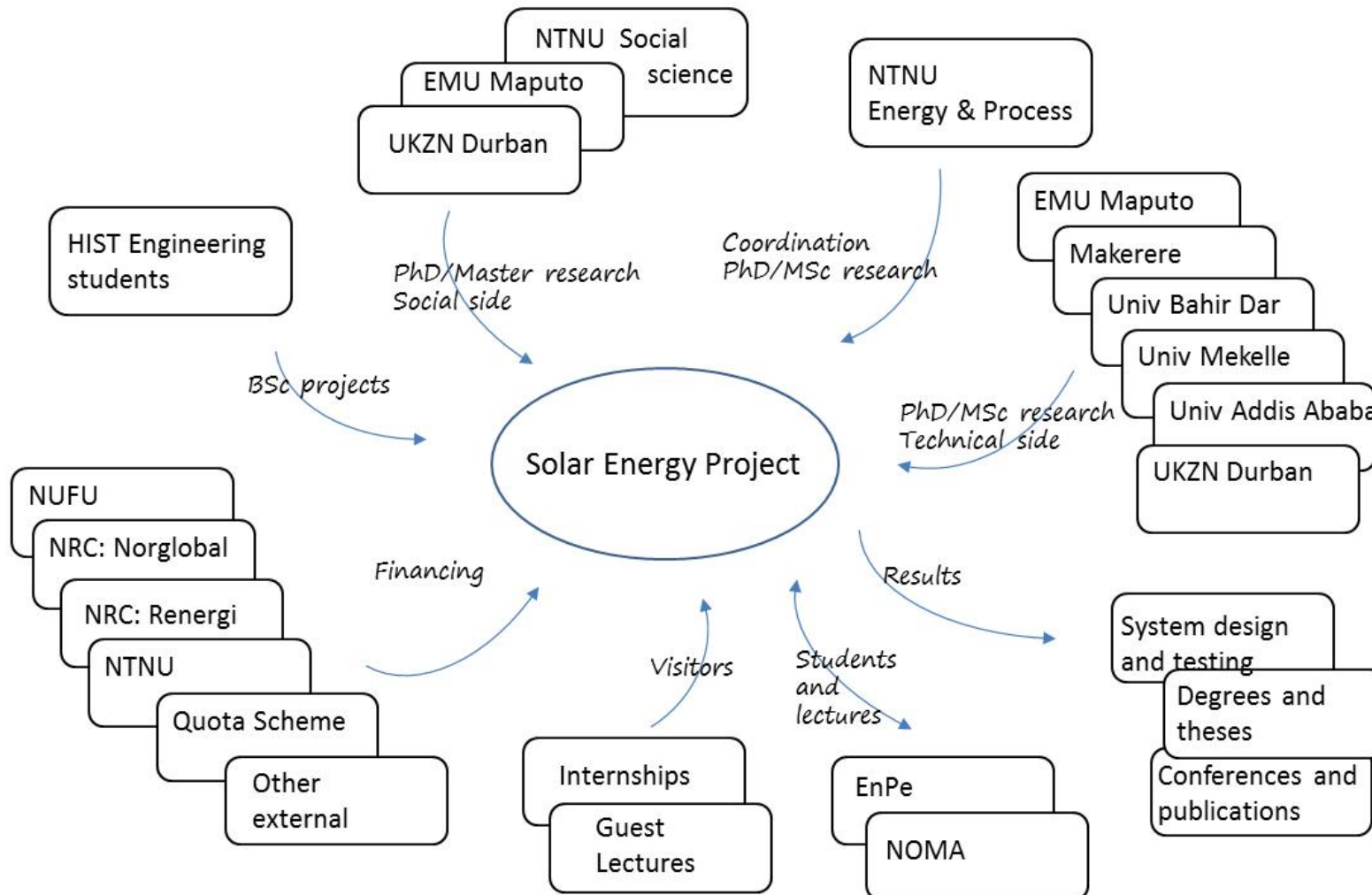


Visits (Maputo)



Joint seminars, NUFU/Noma/EnPe (Dar es Salaam)

# Collaboration





## 5 Motivation

### Energy and environment

Access to affordable energy is one of the basic requirements for development and for poverty reduction. Many areas have about 80% of the population living out of reach of the electrical grid, and where the main energy source is fire wood. Deforestation is already a severe problem, and increasingly so as the population increases.

The objective of our collaboration efforts is to contribute to a shift towards solar energy for thermal energy needs at the level of institutions and households.

### Health

It is the women and children who are at the greatest health risks associated with burning accidents and indoor smoke from fire places. Solar energy should provide a clean alternative for cooking and heating.

### Economy

Solar energy is a free energy source. As the cost of electricity, gas, kerosene or charcoal is rising, the solar alternative should give economic benefits.

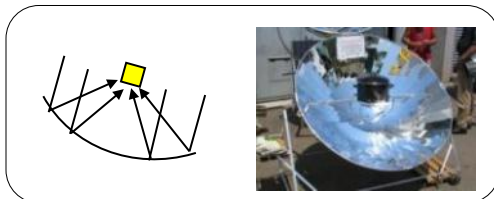
### Gender

Collecting fire wood and food preparation are often laborious tasks for women. A solar system will therefore benefit women in particular, also allowing them time for other activities. The university project also aims at recruiting women for solar MSc studies.

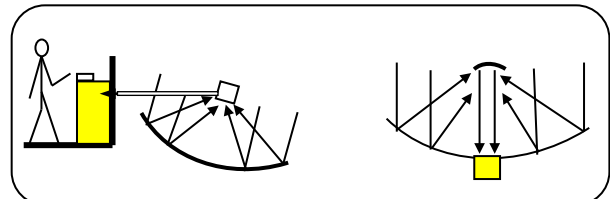
## 6 Concept

The sketch below shows the principles of a traditional solar cooker, in which the cooking pot is placed in the focal point of a parabolic dish. Such systems have been available in many different forms for a long time, but have nevertheless not lead to widespread use. Our focus on including a heat storage and the hope is that addition of heat storage unit may increase the acceptance of solar energy, as it allows for continuous energy use, not limited to the hours of direct sunshine.

Once heat is collected in a storage, it is also available for a wider range of applications.



Established concept for direct solar cookers



Project concept with a heat storage. Heat is transported to a storage, or directly heated

We are testing two types of concepts for including a heat storage in the concentrating solar system.

1) Stationary heat storage

In the first concept, a circulating fluid can carry heat from the absorber and deposit the heat in the storage. We are testing different options for heat carriers (air, oil, steam) and for heat storage (rock bed, oil, phase change material (PCM)). This concept allows for upscaling to larger storage units, to serve energy demands at institutional levels.

2) Heat batteries

In the second concept, the storage can be illuminated directly by the sun rays using a secondary reflector. This storage will be smaller, and portable, typically providing heat for one meal. A larger storage unit can then contain an assembly of smaller heat batteries.



Trough with storage and classical SK14 direct cooker

## 7 Objectives

Our main objective is to study prototypes of small scale concentrating solar heat collectors with integrated heat storage units.

As these are university based activities, the education and collaboration aspects are also important: In particular for the NUFU project the aim is to contribute to the education of young university staff members within the area of renewable energy technology (MSc and PhD studies) and to strengthen the solar research activities, and the laboratory facilities at the participating universities.

## 8 Requirement specification

The initial requirement specification included the following points:

### Energy collection and storage

The solar unit shall track the sun during the day, collect and accumulate the heat in a storage unit. The storage insulation should keep the heat at about 250 degrees C for about 12 hours.

**Simplicity and robustness**

We are aiming at a system which can be produced and maintained with simple means. The system should preferably be possible to assemble based on mass produced components which are readily available (bicycles, cars, agricultural equipment). We search for designs where we can avoid electronic circuits, sensors (temperature or photo diodes) and fragile components. If possible, simple and self-regulating systems are preferred, even at the cost of lower efficiencies compared to what more advanced and optimized systems could give.

**Stand-alone**

The unit shall be operational as an independent unit, not requiring external power.

**Low cost**

The cost level should be such that the system is affordable for small businesses or institutions (schools, hospitals, bakeries, restaurants, etc.). If it is not possible to make a fully mechanical system, some photovoltaic panels will have to be used, in combination with a battery, to power a tracking motor and possibly a circulation motor.

**Safety**

The concentrating solar system should not contain harmful fluids or dangerous parts, nor should it be unsafe to operate. Focusing the sun rays can give very high temperatures at the receiver (many hundred degrees C).

**Applications**

High temperature thermal energy from a concentrator can be used for a larger range of applications than low temperature heat, which can be collected from mass produced flat solar panels. Solar panels can reach boiling temperatures of water. Higher temperatures are required for food preparation (frying, baking) and for power generation (steam). Our first target is for food production, with temperatures in the order of 250 degrees. Baking of the Ethiopian injera bread typically requires heat at about 200 degrees C.

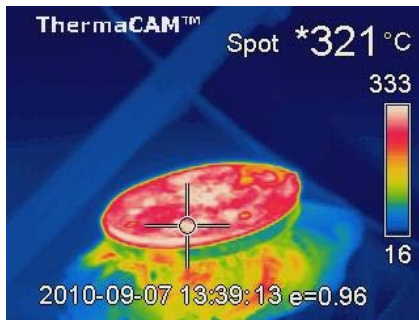
## **9 Methodology**

We combine both experimental work and theoretical analysis. As the work is made in the frameworks of PhD and MSc studies, there is also an educational aspect in addition to the research and development objectives.

### **9.1 Experimental work**

Small scale solar systems are designed, constructed and tested. Some components can be tested separately, before they are assembled into the full system and tested together. This is typically the case for the reflector, solar tracking, absorber, circulation, storage, heat extraction and insulation.

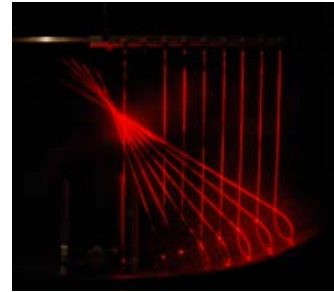
The components are instrumented (typically with temperature sensors) and measurements are made under controlled laboratory conditions. The experimental data form the basis for comparisons with, and tuning of computational models.



Thermal picture of absorber



Rock bed storage test



Reflector test with lasers

## 9.2 Theoretical work

The PhD thesis of Actor Chikukwa includes mathematical models for important components of the system, in particular the volumetric absorber and the heat storage.

We take a system approach to the modeling, where the dynamic conservation equations (1D) for mass, momentum and energy are formulated and integrated numerically in space and time for all the discretized components. A simulation program is written (Matlab) and this constitutes the framework for tuning of particular sub-models (heat transfer coefficients, friction relations, effective heat capacities of phase change materials). After the model is tuned to reproduce the experimental data, it can then be used as a design tool for scale up studies of larger systems and for testing of control strategies. The experimental test versions in our laboratories are smaller versions of the expected field systems.

A ray tracer is developed for analysis of general reflection and absorption systems. The ray tracer can eventually also be coupled to the system model.

## 10 Activities

### 10.1 Technical side

The main objective for the project as a whole is to construct and test solar prototypes. At the start of the project, we discussed specialized tasks for each university. The intention was still that prototypes, as far as possible, should be tested at all universities.

Table 1: Overview of activities in the NUFU Network project

	Maputo	Makarere	Addis	Mekelle	Bahir Dar	NTNU
<b>Heat collection</b>	Dish with mirrors		Trough system Optimization	Dish and trough		Dish and trough with mirrors and film
<b>Heat transport</b>	Air based, once through		Oil	Heat pipes, steam, oil	Heat transport to injera pan	Air, oil and direct
<b>Heat storage</b>	Rock bed	Rock bed Insulation		Oil		Rock bed, PCM
<b>Tracking</b>	Mechanical		Two axis trough			Control systems
<b>Simulation</b>		System dynamics and Ray tracer	Trough and system analysis		Simulation injera pan	System dynamics and Ray tracer
<b>Applications</b>	Food preparation		New injera pan	Sterilization, injera baking	Injera baking	

## 10.2 Social side

Solar box cookers have been available for a long time, but although this seems to be an attractive, low cost technology, it has not gained widespread use. The socio-economic and cultural aspects may be important factors limiting the use of solar heat collectors. The project includes a PhD study from social science on these matters (Pia Otte). Otte did her master thesis work on solar cookers. In a NORGLOBAL project, linked to the Network Project, this type of research is continued, but now on the type of systems we are targeting in this project: somewhat larger in size and with integrated heat storage. The experience from application of Scheffler type of solar reflectors is studied comparatively: Scheffler reflectors are implemented in India, but much less so in Africa.



Gilda Monjane (left) did her master thesis work on solar energy and development (EMU, Maputo)

The social science researchers who are working on the non-technical sides of introducing solar energy systems (including Photovoltaic systems) into a community, have also followed the technical progress of the project, making our research efforts interdisciplinary.

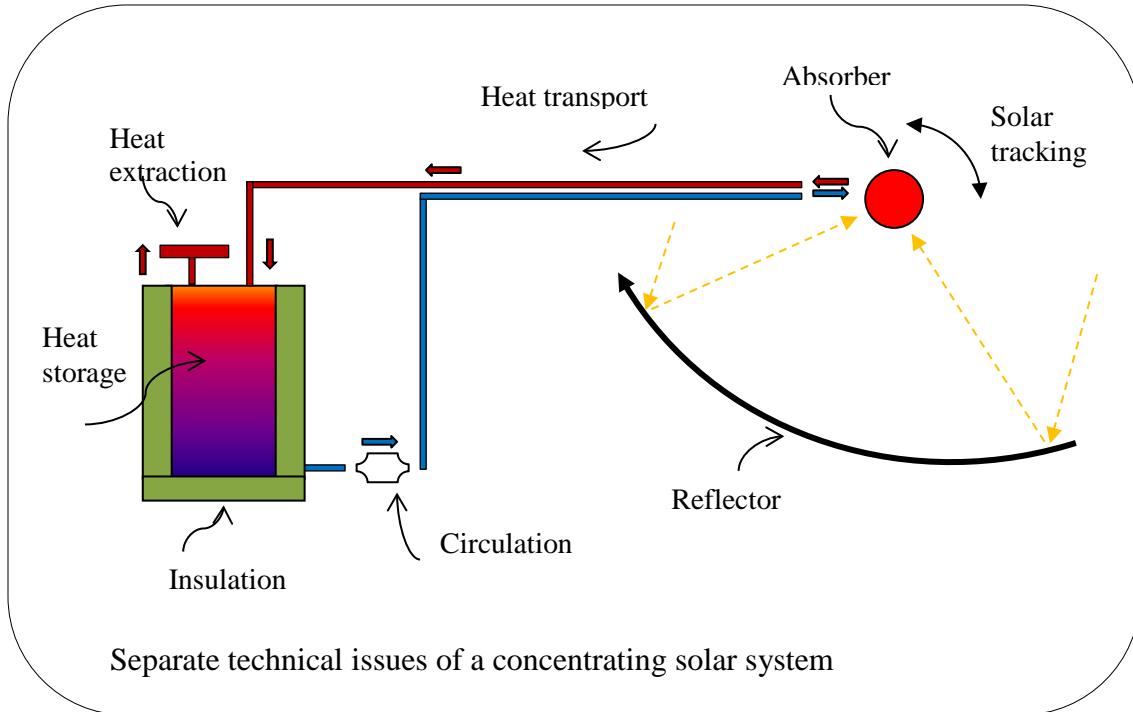
The research methods on the social side are based on field work, with visits to some rural communities using solar energy, distribution of questionnaires and interviews with key stakeholders. In terms of methodology the studies have a combination of qualitative and quantitative research methods, employing different techniques of data collection according to each type of research. When applying qualitative techniques, it relies on observations, interviews, and life stories in order to gather perceptions, experiences, opinions and perspectives about the use and access to the different energy sources with particular emphasis on photovoltaic energy. Questionnaires are used to determine levels of frequencies in order to guide the conclusions

The NORGLOBAL project includes the following studies:

- Cooking with the sun - A comparative study of implementing institutional solar cookers in the developing world (Pia Otte, PhD NTNU)
- A socio-economic and environmental assessment of alternate energy implementation in marginalized areas (Suveshnee Munien, PhD UKZN)
- The role of photovoltaic energy for promotion of sustainable development: case study of two rural communities of Mozambique (Djabula and Tinonganine) (Gilda Monjane, Master EMU)
- Analysis of renewable energy policy: A Contribution to Economic Development of Mozambique (Mery Mondlane, Master EMU)
- Social and economic impact of the use of photovoltaic systems in the district of Moamba-Pessene (Alina AMC Bungueia, Master EMU)

## 11 Challenges

The technical challenges we are faced when designing a concentrating solar system with a heat storage are in principle similar to those for large scale power systems. The different parts are schematically indicated in the figure below



Below follows some comments on the options we have considered, and the experience we have gained.

### 11.1 Reflector

Two reflecting surfaces have been tested. Aluminum parabolic dishes have been covered with mirror tiles and with a reflective film. Glass mirrors are very efficient reflectors, and can withstand wear and tear much better than a film. The focus point on the absorber becomes more widespread, which in our case can have a positive effect of avoiding extreme hot spots on the absorber. Better focusing using a reflective film is needed for multiple reflecting systems. Offset systems, with longer focal lengths, are also sensitive to surface inaccuracies.

The properties of the reflectors have been visualized with an array of laser beams in a smoke chamber. The focal area has been determined with heat cameras. A ray tracer has been useful to study multiple reflector systems, as well as for mirror tiled reflectors.





Tiled trough (Mekelle)



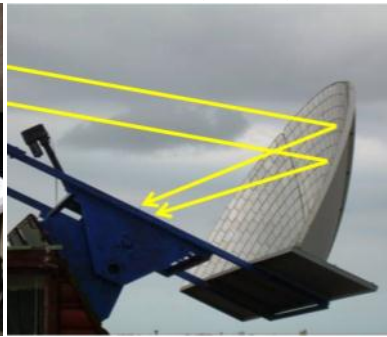
Mirror reflector (NTNU)



Tiled reflector (Maputo)



Baking concentrator (AAU)



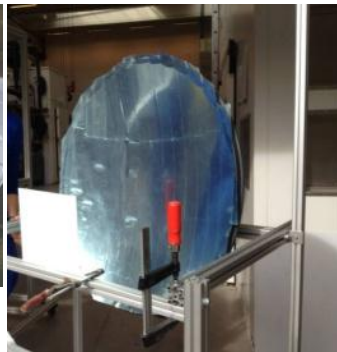
Half dish system (Durban)



Double axis trough (AAU)



Distillator reflector (Mekelle)



off-axis reflector (NTNU)



Double reflector (NTNU)

## 11.2 Solar tracking

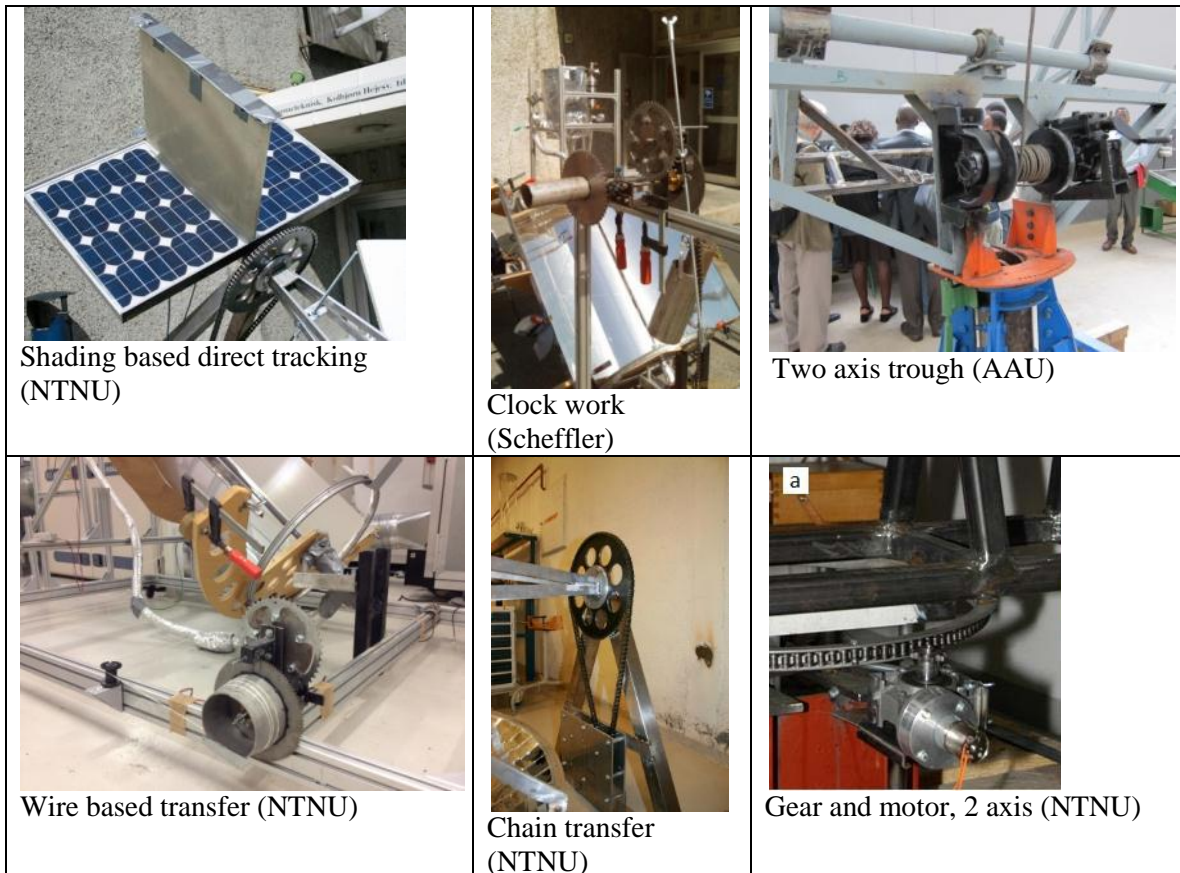
Engineering students from HIST (the local engineering school in Trondheim) have taken their BSc thesis work at NTNU, testing several options for solar tracking. Both single axis and double axis systems have been implemented using small electric motors, a gear system and light sensors.

The control of the motor has been tested with both commercially available controllers and with self-made electronics. A full system control for both the circulation and the tracking has also been designed and partly tested in Durban/Maputo, as well as in Trondheim. A digital controller system allows for easy modifications by programming of a microprocessor.



A direct method was also tested. In this new method, the tracking motor is connected directly to two opposite mounted photovoltaic panels, without any electronics. A shade panel then determines which way the motor shall go. The tracking accuracy with the shading option was about 1 degree, the diode options gave about 0.2 degrees accuracy.

A mechanical clock work was also tested for solar tracking. Some components for the clock work were acquired from the group of Scheffler (Solare-Brücke, Germany). The clock work is quite simple, and it does work if it is sufficiently maintained. Careful calibration (pendulum adjustments) needs to be done, so that the clock works runs at the correct speed.



### 11.3 Absorber

A volumetric fibre absorber for the air system has been constructed based on design considerations by Jørgen Løvseth and Actor Chikukwa. A spherical layer of fibres are located behind a glass cover, such that the air is routed from the illuminated side through the fibres to the inside of the absorber, and further on through pipes to the heat storage. The fibre absorber has also been tested for once through systems (Maputo/NTNU).

The construction demands that the absorber must allow for movement around two axes: the daily rotation with the sun about the polar axis, and declination adjustments of the parabola (every other day) as the sun changes position during the year. Experiments show that it is important that air leakages in the absorber region are avoided. Very high concentration ratios are needed in order to achieve sufficiently high air temperatures (about 300 degrees). A ceramic and a fibre absorber show similar performance.

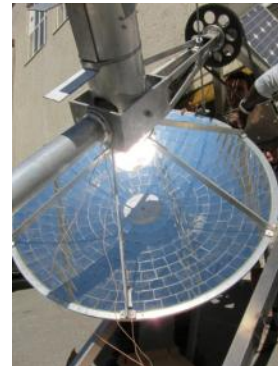
Copper tubes have been tested as absorbers in troughs with a self-circulating oil system. In order to achieve temperatures above 220 degrees at the storage, the absorber had to be covered by a glass tube, to limit the heat losses at the absorber. The heat losses along the pipe absorber in a small scale trough seem to be sufficiently high to avoid overheating of the circulating oil, even in laminar flows. In a dish system, a control system is needed to regulate the focusing and the flow rate of the oil, as experienced by the Durban system.



Oil pipe absorber  
(Durban)



Iron block storage (NTNU)



Volumetric fibre absorber  
(NTNU)



Air absorber test



Focus of a dish (Maputo)



Conduction based absorber



Air based absorber test



Glass covered pipe absorber



Steam generator test

## **11.4 Heat transfer**

### **Air**

Air is a safe, harmless, free and abundant transport medium, but the low density requires a higher flow rate to transport the same energy when compared with a liquid. The heat transfer to and from the air is also a challenge (low flow rates and low heat conductivity).

We have not been able to locate mass produced fans which are suitable for our flow rates and temperatures. The current fan has been constructed in our laboratory, starting from a fan typically used in hot air ovens for kitchens. A variable speed is implemented, to allow for control of the flow rate.

### **Oil**

Heat transfer fluids have been designed to operate at high temperatures, above 300 degrees. They can have very low heat conductivities, comparable with values for insulators, so turbulent flow conditions are preferred. Some have viscosities which are very sensitive to the temperature, and therefore require high pressures in order to flow at low temperatures. Careful safety measures must be made in order to avoid overheating of the fluids, as they are flammable and as they evaporate at some critical temperatures. The temperature gradients near the wall can be large for high energy fluxes and low flow rates.

Oil pump components from cars (AAU) and from motor cycles (Durban) have been tested. Leaks are difficult to avoid, so a recirculation system was adopted in the tests in Addis Ababa.

An option to a pumped system is a self-circulating system. In a boiling system, vapour can be generated at a low point (heat input at the sun receiver), and condense to liquid at a high point (heat output to a storage). The density difference then drives the flow. Density driven flows are also possible for single phase systems (ref. water heating panels). The driving density differences are then smaller, so the pipe friction must be kept lower (larger diameters).

Self-circulating oil systems have been tested in Mekelle and in Trondheim for a pipe absorber and a trough. The Mekelle system used an oil container for heat storage, and the NTNU system used a Nitrate mixture (solar salt) as a phase change material (PCM) in the heat storage. If optimized carefully, even a small scale trough system can provide heat above PCM melting temperatures (about 220 degrees), but the heat collecting efficiency of the system decreases to quite low values at the highest temperatures. Evacuated tubes will increase the efficiency, but also increase the danger for overheating. Tests with a glass tube covering the pipe absorber provided sufficient insulation to reach melting temperatures of the PCM.

Some HTF fluids can evaporate without being destroyed. Self-circulation was tested in a separate setup using Therminol VP-1 and Syltherm 800. The first fluid was difficult to work with, and was eventually abandoned, due to a very strong smell and irritating effects. The fluids are also costly, and not easily obtained everywhere. The second fluid did not behave as expected, the boiling could not be observed at the expected temperatures. Boiling-condensing system was therefore in the further only considered for water systems.



Light guide test (NTNU)



Motor and oil pump (AAU)



Motor and oil pump (Durban)



Air fan (NTNU)



Air fan (Maputo)

### Steam

A setup was made and tested where water was boiling at the absorber and steam was condensing in the storage. Initiation of the system was made by heating a water filled system, and evacuating water as steam was generated, until a suitable amount of water remained. Water has a very high heat of vaporization and is harmless and abundant, and boiling and condensing heat transfer is very efficient, so only small mass flows are required. The drawback is that the system needs to be pressurized at about 40 bar, to reach about 250 degrees C. So the amount of water needs to be small and confined to heat transfer pipes which then exchange heat with a storage medium. Large pressurized water tanks will be too dangerous, as tank failures can give steam explosions.

A direct steam generation system was also tested for the application of solar sterilization in Mekelle. A modified pressure cooker was positioned directly in the focal point, to generate steam for the internals to be sterilized.



## Lightguide

Heat transfer from the focus point to the storage in the form of a light guide has also been briefly considered. This would be an attractive heat transfer solution, if optical losses could be avoided (as in the case of optical fibres, where total reflection at the wall gives light propagation without losses). A light channel was constructed from mirror tiles and tested with a dish reflector. The internal losses were too large. The square channel, and the diverging rays at the inlet were far from optimum conditions, but the results were so weak that the concept was not been explored any further.

## 11.5 Heat storage

We have obtaining experience with two types of heat storage methods: sensible heat in a rock bed (Makerere/NTNU) or in oil (Mekelle/NTNU), and heat stored in a phase change material (PCM), and combinations of both (NTNU).

### Rock bed

Rocks have been used as a storage medium for low temperature heat in buildings. The thermal conductivity of the rock is low, so once heat has been accumulated in a rock it does not easily leave the rock by conduction. A rock bed can therefore be an inexpensive heat storage option, but a circulating fluid is needed for heat exchange to and from the rocks.

Experiments have been made with artificially heated rock beds (temperature profiles and pressure drop). A potential benefit of such storage systems is that thermal stratification can be achieved, where the upper part with the heat inlet is hot and the lower part is cold. Charging and discharging could then ideally be in the form of a temperature front moving up and down in the storage. Discharging with cold air from the bottom, will give heated air at the top outlet. With a controller on the fan, the inlet temperature during charging can be regulated to desired values.

With 40-50 cm storage lengths and a charging temperature of about 300 degrees C, the thermal stratification is quite weak. The degradation of the temperature profile also takes place in time, the internal heat conduction is low but will eventually bring the storage to uniform temperatures during an over-night period. To benefit fully from stratification, the storage needs to be significantly longer.



River bed rocks



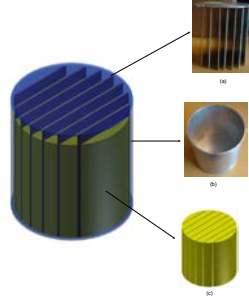
Rock bed container (NTNU)



Oil based storage (Durban)



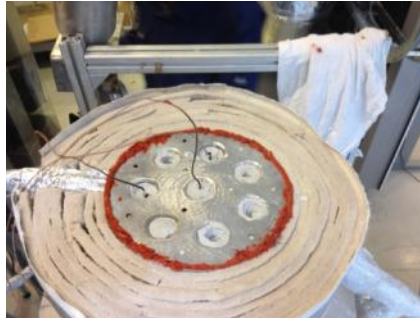
PCM containers (NTNU)



Filling with PCM



Aluminum with PCM cavities (NTNU)



Oil with PCM cylinders



Filling PCM in cylinders

A rock bed charged with a circulating oil has been considered in a previous project at UKZN, Durban.

### **Solar Salt PCM**

A PCM stores the heat by phase change, it takes heat to melt a substance and the heat is regained when it solidifies. The latent heat can be quite large, and increase the heat storage capacity by a factor of 4 or more compared to sensible heat options. "Solar Salt" is a term for a Nitrate mixture which is designed for use in solar systems. The melting point is about 220 degrees C, which is in the suitable temperature range for frying and baking.

The solar salt has been difficult to obtain in Ethiopia, so the storage tests have been made at NTNU. Two different storages have been constructed and tested.

### ***Direct charging of a Solar Battery***

A cylindrical Solar Salt storage has been constructed with a top plate having conducting fins extending down into the salt storage. The storage can then be charged by illumination from the top (in a double reflector system). After charging the storage can be removed and used as a transportable cooking plate.

Food preparation (frying and boiling) has been tested on a charged storage. The principle of combining heat batteries to serve larger application was tested by an attempt to connect four storage units together, with a large 50 cm diameter frying pan covering the

four top plates. One attempt was made to bake injera on the frying pan, but the heat transfer between the plates just resting on top of each other was weak, and not optimized. The baking of quality injera from 100% teff flour has not been well proven on a metal surface. Frying of wheat pancakes was easier to demonstrate.

A final efficiency measurement for the heat storage in a double reflector system needs to be completed (2013).

### ***Charging with hot air***

As a rather quick test, four PCM cylinders were immersed into a rock bed to be charged with a heated air flow. The rock bed would then serve as a heat exchanger to the PCM storage. Heat should then also be extracted by conduction to a top plate attached to the cylinders. The cylinders do thermally short cut the heat storage which reduces the stratification – but the stratification in our short bed was rather weak to start with.

### ***Charging with oil***

A PCM storage unit was constructed to be charged by the trough system with a self-circulating oil. It is important that the flammable oil does not come in contact with the Nitrates, so the storage was made of an oil cylinder in which aluminium cylinders with the salt are immersed into. The cylinders are welded together with a top plate, to become one unit. The oil can then not come in contact with the salt.

This combined oil-salt storage was tested in a small scale trough, and the self-circulating system was able to melt the salt.

### ***Charging with steam***

A storage unit was made out of an aluminium block. Cylindrical cavities were drilled for the salt and other holes drilled for the steam channels. The heat transfer is limited by the low heat conduction in the salt, so the amount of aluminium can be adjusted to provide a thermal buffer for applications, e.g. frying on the top plate.

The storage was first tested with oil charging and compared with the other storage with aluminium cylinders, the latter showing a better performance.

Steam charging of the aluminium block with salt was tested in a separate setup and in a dish system in the sun. The idea with the design is that the steam channels should be pressure safe (40 bar operational pressure at 250 degrees C), the salt cavities should be well separated from the steam channels, good heat transfer to and from the cavities and the channels and the aluminium should provide a heat buffer for frying application.

## **11.6 Insulation**

Insulation of small scale, high temperature heat storage units is a challenge. We aim at storing heat at temperatures around 250 degrees for about 12 hours. Standard insulation material becomes very bulky. A second version of a rock bed storage tank was constructed with double walls containing several layers of reflecting materials. Attempts with evacuating the air between the two wall layers were made, without convincing results. Vacuum insulation requires very low pressures, which puts high demands on the construction of the system (welds, purity).

Several natural occurring candidates for insulation material were considered at Makerere (rock, ash, clay). Insulation remains as a weak point in the solar thermal system. We have used aerogel in our laboratory tests, but that is quite expensive, leaves irritating dust, and is not easily available everywhere. Rock wool and glass wool lost the binding structure when heated to about 400 degrees C.



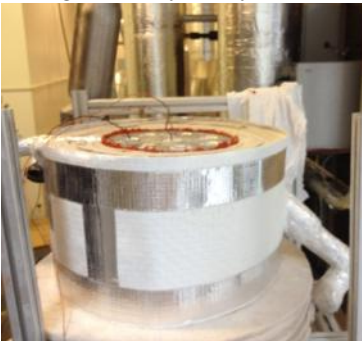
Aerogel is very dusty



Glass wool



Aerogel



PCM/Oil



Aluminium and PCM



Ceramic insulation rock bed

### 11.7 Heat extraction

Heat extraction from the storage to an application is a separate challenge. It should ideally be possible to regulate the heat transfer. A high power is needed to bring water to the boiling point, but less power for the subsequent boiling of the food.

A storage charged with a heat transfer fluid can potentially use the same method for heat extraction as for the charging. A self-circulation loop can be made for the application, where the fluid is heated in the storage and cooled in the application. For the single phase case, oil could be pumped and air could be blown as in the charging case.

#### Air

Heat extraction tests for the air based rock bed were made by reversing the flow, such that hot air was circulating under a finned top plate of the storage. Cooking was tested on the top plate. It was demonstrated how the air blower could then regulate the power to the plate.



## Oil

A new injera baking pan has been made and tested in Addis Ababa. The pan was positioned on top of a finned plate, which was immersed into a bath with circulating oil. The oil was artificially heated in the tests, but the oil could be supplied either directly from a trough or from a heat storage unit. Injera baking was successfully demonstrated on the system.

## Steam

Two self-circulation tests have been made to test condensing heat transfer at a cooking plate. A coiled pipe was clamped between two aluminium plates and fed with vapour from boiling Therminol-VP1 in one case and Syltherm 800 in the other case. The attractive feature of using boiling heat transfer is that the temperature can be adjusted by controlling the pressure, as the vapour will be at saturation conditions. The heat extraction rate may be regulated with a circulation valve.

Heat extraction by steam from a heat storage has not been tested within the project period. An aluminium plate has been casted with a coiled pipe inside, and the plate is ready for testing by coupling it to a heat storage.



Cooking on top of PCM/Oil storage (NTNU)



Condensing heat transfer test to top plate



Oil circulation to baking pan (AAU)



Fins in rock bed



Assembly of four PCM containers (NTNU)



Top plate on four PCM containers

## Conduction

Heat transfer from a storage to a cooking plate can be made by conduction through fins. This was tested for a rock bed heat storage. Conducting aluminium fins were connected to a top plate and immersed down into the whole length of the rock bed. The fins will

short cut the heat storage, by allowing rapid heat transport through the fins from the top of the bed to the bottom. This will destroy a thermal stratification effect, however, as for the PCM cylinder case, the argument could be that the stratification is weak in the first place.

A two compartment storage unit is planned for testing in Maputo, where the first compartment is for high temperatures and the second for the residual heat (lower temperature heat for water heating).

Conduction is also the concept for the PCM storages we have tested. The heat extraction is then by heat conduction to the top plate, which serves as a cooking plate.

### **11.8 Control**

There are two needs for control: solar tracking and a control method for the heat charging/extraction system, including safety systems.

The solar intensity is changing during the day, and during the passage of clouds. For the air and the oil system this means a flow controller is needed to obtain a temperature set point at the storage inlet. The air fan should only drive the flow from the absorber to the storage when heat is available at the absorber. When the direct sunshine disappears, or the reflector is out of focus, the fan should stop, in order not to cool the storage

Maputo has worked on a unified control system, based on temperature sensors and microprocessors. A smaller system has also been constructed by engineering students at NTNU. There is need for simplistic systems, preferably not depending on temperature sensors.

Two types of self-regulating systems have been considered.

A very simple method is to put a threshold on the PV panel powering the circulation motor. By positioning the panel in the focal plane, which follows the tracker, it will provide power when in focus, and shut down when out of focus, or during cloud cover. The system can be optimized by adding an intensity reducing film on the PV surface, and also trough arrangements with shading panels.

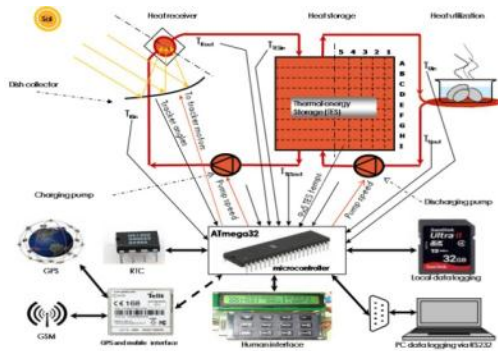
Another method could be to attach a thermal engine to the focus point. Then the engine will drive the circulation only when the absorber is hot. A Stirling engine has been built for this type of testing, but not integrated and tested with the solar system yet. The challenge with a Stirling engine is the efficiency, the power is often low.

### **11.9 Radiation measurements**

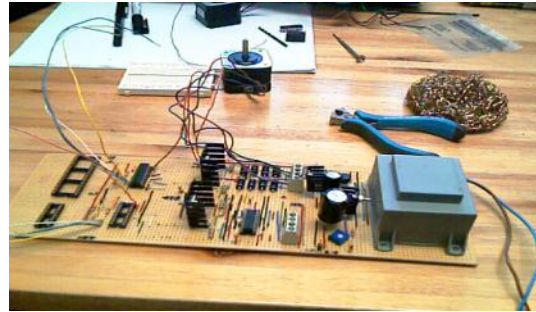
The project has included two types of activities on solar radiation. One is a PhD candidate in Maputo/Durban who has worked on development of a low cost instrument for radiation measurements. Long term radiation measurements at various locations across the countries are important in order to assess the solar energy potentials in each region. A low cost instrument would be useful for this purpose.

The candidate works in collaboration with UKZN, Durban.

The other activity has been to install and monitor radiation measurements at several locations in Uganda. The data has been used to calibrate radiation models, which can provide expected averaged radiation intensities in the different regions and different times of the year.



System control (Durban/Maputo)



Low cost radiation instrument (Durban/Maputo)

## 11.10 Computational models

### System model

A computational framework has been established for the whole system consisting of the absorber, the pipe connections and the storage (Makerere/NTNU). The model is based on numerical integration of 1D conservation equations for mass, momentum and energy. The implementation is in Matlab. The time evolution of the temperatures at all nodes can be computed from the given initial and boundary conditions.

The PCM storage is modeled using an effective heat capacity in the melting region, based on measurements from the laboratory. Effective heat conductivities and friction relations for the rock bed are tuned to the experimental data (temperature profiles and trends, pressure drop).

The thermal heat collection system has large variations in time responses, the absorber and heat transfer pipes can be considered as steady state in comparisons with the slow charging and discharging of the storage. The framework does, however, allow for dynamic studies also for the absorber and the heat transfer pipes, which can be useful for the case of a trough reflector with a long absorber pipe.

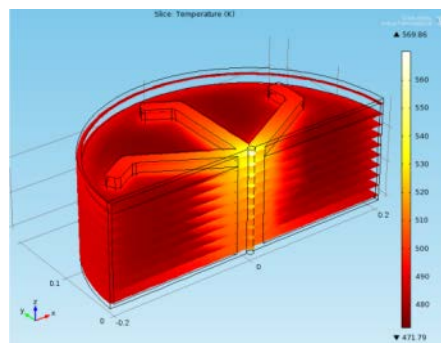
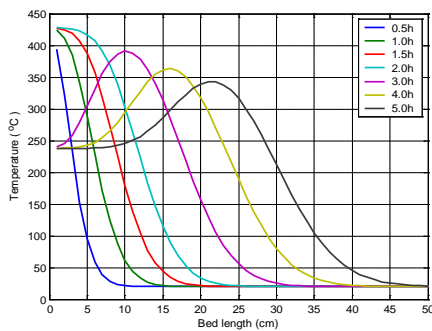
A simplified model has also been established and compared with experiment on the self-circulating oil in a trough collector.

The strategy for the modeling work is to establish a computational framework for the integration of the conservation equations. Heat transfer and conductivity models can then be tuned to experiments and the model can then be used as a design tool for up-scaling of the systems.

**Heat conduction analysis**

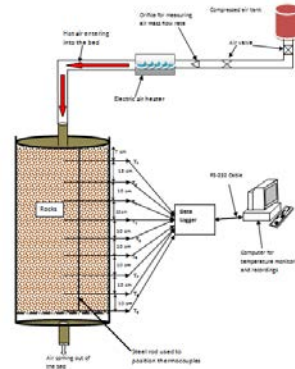
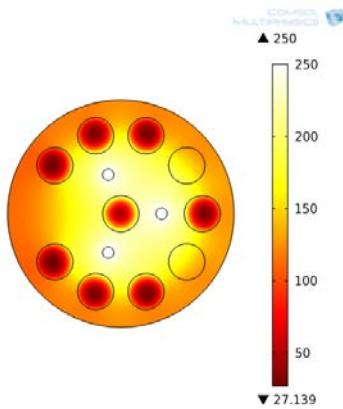
For the case of direct illumination of a PCM storage, it has been useful to make use of COMSOL Multiphysics for conduction analysis. Effective heat capacities can be implemented to simulate the phase change. The simulations have been used to determine fin thickness and fin densities in a PCM storage.

A heat transfer analysis of the injera pan has also been made by a finite element method (Addis).



Simulations: Dynamic charging of rock bed (Makerere)

Heat conduction analysis (NTNU)



Heat conduction Aluminum, PCM cavities and steam channels

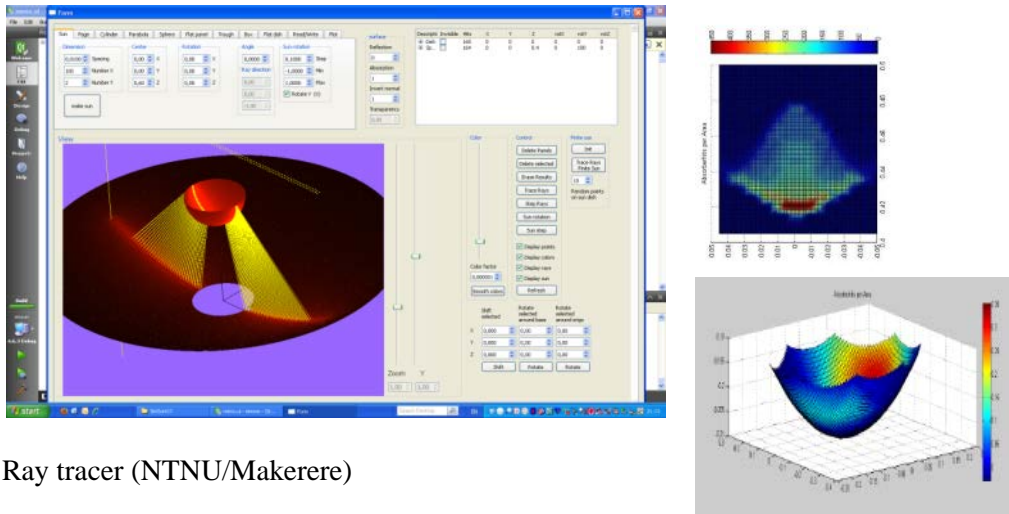
System model: computations and experiments (Makerere)

**Ray tracer**

A ray tracer has been developed, for analysis of general reflection and absorption systems (Makerere/NTNU). A sun is defined and emits rays which are traced in 3D through the reflection systems until they hit an absorber or are lost. When a parabola is represented with a number of flat mirrors, and when we study off-focus situations, we have a 3D problem which can be analyzed with a ray tracer.

The ray tracer can be useful in quantifying how the losses (interception ratios) varies with the size of the mirror tiles, how the intensity distribution changes along the absorber, sensitivity to off-focus angles and sensitivities in multiple reflecting systems.

The first version was developed in Matlab, the second in C++ with the Qt library for making the graphical interface (GUI). A test with GPU programming of the core gave large speed-up benefits.



Ray tracer (NTNU/Makerere)

## 12 System tests

### 12.1 Air based system

A first air based system was constructed and tested at NTNU, based on the theoretical design and analysis as documented in the PhD thesis of Actor Chikukwa, under supervision of Jorgen Løvseth. A larger system is still to be tested at EMU, Maputo. The system collects heat in a fibre based absorber at the focal point of a mirror tiled dish. The dish is polar mount, with single axis tracking and a chain based gearing system. A fan circulates the air through a rock bed heat storage. The storage has fins extending from the top plate, so heat extraction is by conduction.

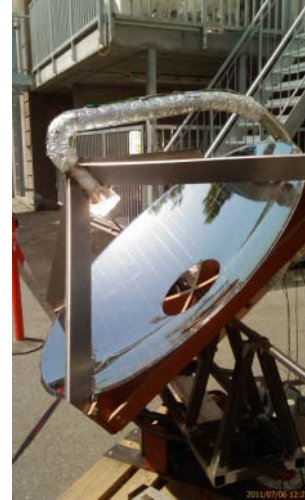
The tests gave rather low temperatures, about 150 degrees C. The absorber was initially designed for a 2 m diameter dish, but was installed on a smaller 1.2 m diameter dish, giving a lower concentration ratio. The heat collection performance of smaller absorbers, and a film covered dish collector gave temperatures in the target range, up to 3-400 degrees C out of the absorber.

The small scale tests are completed at NTNU, but work on the air based system will continue in Maputo, using a larger dish collector.





Air/rock bed test



Absorber test

### 12.2 Oil based system

A small scale trough system, with a copper tube as a heat absorber, has been constructed and optimized. The reflecting surface is a smooth aluminium sheet (reflectivity about 90%). A tracking system supplied by the Scheffler group was extended with a wire transfer to a single axis trough rotation. The system has been tested with heating elements on the absorber and in the sun and with two design options for PCM heat storage units (Solar Salt). Heat extraction for food preparation will be by conduction to the top plate. The oil (Duratherm 600) is self-circulating due to the density difference between cold and hot oil.

The heat losses at the absorber are a critical point, as with all concentrating thermal systems. To reach melting temperatures in the storage the absorber needed to be shielded with a glass cover, to reduce the convective losses. The salt could then be melted by the self-circulating oil. Further optimization should be possible by using an evacuated absorber tube. The experiments compare well with a computational model.

A mirror tiled trough has been tested with self-circulation of oil at Mekelle. The experience is the same that the losses at the absorber is critical. The small scale trough system is sufficiently investigated. Further work could be on field testing and on scale-up studies.



Trough with Oil/PCM storage (NTNU)



Trough with Oil/PCM storage (Mekelle)

### 12.3 Direct system

#### Heat batteries

Solar Salt containers (about 20 cm diameter), with fins extending from the top plate into the salt have been analysed, constructed and tested. The first solar salt cylinder was smaller and tested in a double reflector concentrator, where a secondary reflector above the focal point redirects the rays back through a centre hole in the primary reflector and hits the stationary storage unit below. The storage is then easily accessible and outside the reflection area of the primary dish. The storage is heated by the illumination of the top plate and the storage can, after charging, be removed and used wherever needed. The test in the sun melted the salt, with a top plate temperature of about 300 degrees C. The second design of the heat storage was larger, and only tested with artificial heating (winter time in Norway). A new 2 m diameter film covered dish has been made with a two axis tracking system. A final efficiency measurement of the double reflector and heat battery concept will then be made. Further work would then be on optimization of the insulation methods and on field tests of the concept.



New double reflector  
to be tested

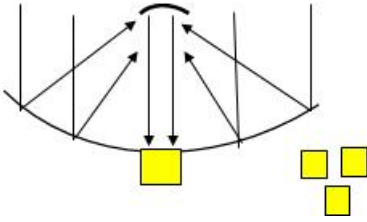
Double reflector test

#### Off-set parabola

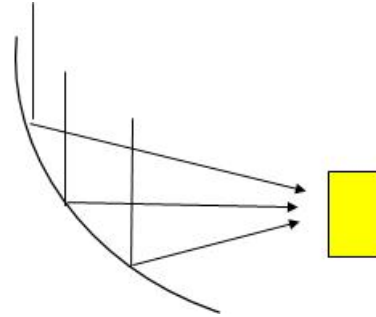
A Scheffler type of off-set parabola in combination with a stationary solar salt heat storage could be an interesting concept to evaluate. The Scheffler system includes a modification of the shape of the reflector, during the seasonal change in the declination of the sun. Although tested and proved for very many years, the system does become somewhat complex and requires skilled maintenance people.

Some investigations on a frozen Scheffler dish have been made using a small scale offset antenna, and using the ray tracer. The ray tracer has been extended to include Scheffler reflectors, with tiled or smooth surfaces.

Further work on a Scheffler type of concept is for the future.



Double reflector system with small heat batteries



Scheffler type offset parabola with larger heat storage

### 12.4 Steam based system

Steam based heat transfer to the heat storage has been partly tested. Some tests have been made with the aluminium block and PCM cavities (NTNU). Steam has also been generated in a dish and fed into a coiled pipe imbedded in an injera pan (Mekelle). An offset system is also under testing in Durban. This system reduces the heat transport problem by generating steam much closer to the storage. The system can be wall mounted.



Steam based test unit (NTNU)



Steam generation and coupling to baking pan (Mekelle)

## 13 Applications

### Injera baking

Injera baking is one of the target applications for a solar heat collection system. A concentrating system is needed, in order to reach the required frying temperature of about 200 degrees. Injera baking is traditionally made on a clay pan (mitad), positioned over



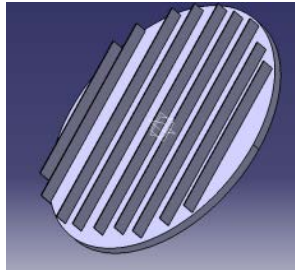
open fire. As the clay is a poor heat conductor, the pan requires long heating times, which results in poor efficiencies and wasted energy.

Attempts have been made to investigate other frying materials than clay, metal pans would be more suitable for integration with heat transfer pipes. Heat transfer analysis of the clay pan has been made in Addis Ababa. Practical frying tests have been compared using electrical clay pans, glass pans, Teflon coated aluminium pans and cast iron pans (including the traditional Norwegian "takke"). It is still not clear whether the problem is a surface problem (sticking) or a heat transfer problem (baking process to yield the air cavities in the injera).

A new injera pan has been designed, constructed and tested at AAU. This is a ceramic based 8 mm thick pan, which is positioned on top of a circular metal support. The traditional clay mitad is about 20 mm thick, so energy savings are achieved with the new ceramic pan. The metal support allows for interfacing with a heat transfer fluid, and successful injera backing tests have been made with a circulating oil.



Standard clay mitad for injera, electric



Support for new ceramic mitad (Addis Abeba)



Injera on new mitad



Oil powered new mitad (Addis)



Injera baking electric mitad



Injera baking open fire

### Test sites

Some steps have been taken in order to identify field test opportunities.

Hospitals can be a suitable target institution, as a hospital requires energy for a range of applications: food preparation, steam for sterilization, hot water, refrigeration.

The energy needs of a particular rural hospital in Tanzania (Haydom hospital, Arusha region) have been reviewed and it is regarded as a suitable test site. The hospital has work shop capabilities and receives support from NORAD (Haydom Regional Project).

The energy sources at the hospital are largely diesel, fire wood and electricity (unreliable).

A hospital in Arba Minch, Ethiopia, is also a candidate for testing of a new solar system. The energy consumption is largely from electrical power, but the electricity is a significant operational cost and the reliability is uncertain. The hospital cooks food and bakes a large amount of injera for the patients. A smaller hospital in Gidole, south of Arba Minch, is also a possible test site. The energy source at Gidole is mainly fire wood.

Other hospitals and health stations have been visited. One interesting observation is that even quite small units had positive experience with outsourcing of services (kitchen, cleaning, laundry). Outsourced services may be more at tentative to new solar technology which can potentially provide savings.



Wood fired cooking stoves  
(Ginnir hospital, Ethiopia)



Open fire food preparation for  
patients (Haydom hospital,  
Tanzania)



Wood fired boiler  
(Gidole hospital, Ethiopia)

## 14 PhDs

<b>Rock bed thermal energy storage for solar cooking application</b> (Potential for solar cooking in Uganda)	
Denis Okello - 2012	
Makerere University	Supervisors: Eldad J. K. Banda and Ole J. Nydal

**Objectives**

The objective is to develop and test an air-based rock-bed Thermal Energy Storage (TES) unit for solar cookers and evaluate the potential of such systems in Uganda.

**Tasks**

1. Model the distribution in the daily amount of solar radiation in Uganda
2. Develop a model of spatial and temporal distribution of direct solar radiation in Uganda
3. Validate a modified 1-D Schumann's model for an air-rock bed system with experimental results.
4. Perform energy analysis of an air-based rock bed TES for different charging and discharging methods.
5. Optimize the storage size of an air-based rock-bed TES
6. Compare existing pressure drop correlations with experimental results.

**Results**

In Uganda, solar radiation is distributed throughout the year with higher potentials in some periods. Relatively lower sunshine duration is registered in southern and south-western part of Uganda.

Rock bed storage systems were constructed and the temperature profiles were measured in time during charging and discharging tests. Electrically heated air was used for charging, with varying the flow rate and the temperatures. The modified Schumann's model is observed to predict the temperature profiles as a function of charging time with a mean percentage error of 16%. Discrepancies between the experimental and simulated responses were mainly due to the uncertainties in the measurements, heat losses and modelling assumptions.

Smaller particle sizes give smaller averaged void fractions, which promote stratification but increase the pressure drop and the blower power requirement.

The thermal degradation in a highly stratified rock bed thermal energy storage system is faster in the high temperatures region.

It is possible to use both phase change material and rocks in an air based system.

Incorporating phase change materials in a bed of rocks increases the energy content of the bed but shortcuts the storage thermally and reduces the stratification.

The discharging rate to a cooking pot at the top plate can be varied by varying the reversed air speed through the bed.

The pressure drop is a strong function of air flow rates and particle sizes. The Dunkle and Ellul correlation gives a conservative estimate of the pressure drop in an air-based rock bed system with random packing of bed particles.

<b>Dynamic Model for Small Scale Concentrating Solar Energy System with Heat Storage</b>	
Karidewa Nyeinga -2012	
Makerere University	Supervisors: Eldad Banda and Ole J. Nydal

### ***Objectives***

The main objective of this study was to develop analysis tools for concentrating solar systems with integrated heat storage units (TES). The model can be used as a design tool for a solar oven system. This will enhance the development of a proto-type that can be tested in the rural community. The specific objectives were:

- To develop a transient computational model for high temperature heat collection system with a rock bed heat storage system using air as the heat carrier.
- To study the effect of fan control for charging a solar TES system during periods of intermittent sunshine.
- To simulate a combined PCM (Phase Change Material) and rock bed thermal storage system and assess how it improves thermal energy storage.
- To develop and demonstrate a ray tracer tool for analyses of general solar concentrating systems.

### ***Tasks***

The research focused on the development of a dynamic model for solar thermal storage systems at high temperature. The model is based on numerical integration of a set of conservation equations for mass, momentum and energy of the heat carrier, the rock pebbles and the walls. The numerical solutions are implemented based on implicit time integration without iterations. Stability problems at large time steps do not occur. The model predicts pressure, air velocity, air density and temperatures of the air, rock bed and wall in time and along the container.

### ***Results***

The findings of the research include:

- A numerical model that can be used as a design tool and for operational work has been developed and tested in a Matlab implementation.
- A ray tracer for analysis of solar concentrating systems has been developed. An algorithm for a parabolic reflector with a continuous surface was developed in 3D and implemented using Matlab.

<b>Development and Performance Analysis of a Solar Stove Prototype With Heat Storage</b>	
Amós Veremachi - 2013	
Eduardo Mondlane University	Supervisors: Boaventura C. Cuamba and Ole J. Nydal Advisor: J. Løvseth

### *Objectives*

- Investigate the optical performance of a mirror tiled parabolic dish sun collector.
- Design an optimal receiver for the air based heat transfer system
- Investigate the thermal performance of the collector.
- Investigate thermal performance of a two stage rock bed heat storage system.

### *Tasks*

- Design, construction and testing of an air based heat collection system
- Experimental determination of the location of the focal point (laser based mapping of the reflections from the concentrator surface on the focal region)
- Construction of different absorbers (in size and shape)
- Measurements of temperatures at absorber surface, of the environment and of the air leaving the collector by means of thermocouples connected to data acquisition instruments which in turn is connected to a computer (logging temperatures).
- Construct a rock bed heat storage and test its thermal behavior (to be done!)

### *Results*

- For the volumetric receivers, concentration ratios ranging from 119 and 476 were achieved.
- The absorber for which a concentration ratio of 476 was achieved, a temperature of around 350° C and thermal efficiency of 16 % were possible.
- A Poster based on preliminary tests on the collector was presented and its corresponding full paper was submitted for the conference proceedings of Kassel Solar World Congress in 2011

The PhD will continue in 2013

<b>Self-circulating liquid based solar collector with heat storage</b>	
Maxime Mussard - 2013	
Norwegian University of Science and Technology	Supervisors: Ole J. Nydal, J. Løvseth

**Objectives**

The objective is to design and test a solar cooker able to store energy over 200°C. The system must be cheap, robust, efficient, without health hazard, easy to make and to use. The high temperature enables frying as well as cooking.

The systems tested are gravity driven. The sun heat is absorbed with a parabolic trough an absorber tube which contains thermal oil. The heated oil flows up by gravity difference to the storage, and comes back once cooled to the inlet of the absorber in a closed loop.

**Tasks**

The research tasks are:

- Design and construction of a small scale solar parabolic trough with its tracking system
- Study the influence of tracking inaccuracy on the performance of the system
- Dimensioning of the heat storage, comparison between sensible and latent heat storage methods
- Testing and simulation of a closed self-circulating loop heated by the solar trough
- Comparison of aluminum and oil-based heat storages with phase change materials (PCM) heated electrically
- Experimental testing in the sun of the storage coupled with the collector and the self-circulating loop, and numerical simulation
- Heat extraction test with cooking and frying. Comparison with a widespread direct solar cooker
- Up scaling studies of the system

**Results**

- Sufficient tracking accuracy is obtained with Scheffler type sensor and motor
- Self-circulation appears to be efficient enough to carry the heat from the absorber to the storage in the intermediate temperature range
- An oil-based heat storage coupled with PCM cylinders will optimize the heat storage and be more efficient than an aluminum-based system with PCM cavities
- The original system proved to be able to store energy by melting salt at 220°C.
- The heat extraction for food preparation was tested by boiling one liter of water and frying a piece of meat.
- A computational model was developed and compared with the measurements. Numerical simulations show that up scaling is feasible if the system is carefully optimized

<b>Concentrating solar system with heat storage for small scale applications</b>	
Asfafaw Haileelassie Tesfay - 2014	
Norwegian University of Science and Technology	Supervisors: Ole J. Nydal, Mulu B. Kaysay

***Objectives***

Design, produce, test and analyze a robust small scale solar baking pan (Mitad) with a high temperature storage.

The specific objectives are to arrive at:

- A steam based self-circulating heat collection system with a single axis solar tracking method
- A suitable high temperature heat storage for small scale solar thermal applications
- A heat transfer method from the storage to the Mitad
- A solar Mitad which can be proved to work for injera baking (Ethiopian bread)
- Comparisons of experimental data and computational models

***Tasks***

The research will include the following main tasks:

- Building a high temperature concentrator with a fixed focus and a tracking mechanism
- Steam as heat transporting fluid (HTF)
  - Experimental study of closed loop boiling-condensing steam system to carry heat from the receiver to storage
  - Experimental study of a closed loop boiling-condensing steam system to carry heat from storage to stove
  - Modeling the boiling-condensing closed loop steam system
- High temperature heat storage (200-250°C),
  - Design and optimization of t Nitrate (PCM) based heat storages for small scale applications
  - Temperature measurement and studies of the heat transfer
- Computational system analysis
  - The design and prototype development of the system is accompanied by computational tools for comparisons with experiments and for optimization of the system.

***Results***

The expected results of this study will be a prototype of solar steam Mitad with documentations of test results in publications and presentations at conferences.

<b>Investigation of small scale solar concentrating parabolic dish with heat storage</b>	
Habtamu B. Madessa -2011	
Norwegian University of Science and Technology	Supervisors: Ole J. Nydal Advisor: J. Løvseth

### ***Objectives***

The objectives of the work is to design, construct, test and analyze a small scale concentrating system with air based heat transfer to a rock bed heat storage

### ***Tasks***

The tasks have included

- Construct an instrumented prototype heat collection system (mirror tiled parabolic dish) with a rock bed storage
- Measure the performance of the system components and the integrated system
- Analyze the tests in comparisons with a dynamic system model and a ray tracer
- Conclude on the feasibility of the system as energy supply for food preparation

The work is mainly experimental and has been undertaken in the NTNU laboratories. The rock heat storage was tested using an electrically heated blower. A solar simulator (array of lamps) has been useful for testing of flat plate heat collectors, but turned out to be difficult to use for concentrating systems. The testing of the absorber and the solar tracking system has therefore been to the summer season in Trondheim.

### ***Results***

- A single axis, polar mounted solar tracking system based on shading of solar panels driving a tracking motor directly gave about one degree tracking accuracy. For a spherical absorber this was of sufficient accuracy.
- The time evolution of the thermal profiles in the rock bed during charging could be reproduced with a 1D dynamic thermohydraulic model (Matlab implementation).
- A ray tracer (Matlab implementation) was used to investigate the light transport in a square, U-shaped channel made of mirrors. The lightguide was too inefficient, with much backscattering and losses due to many internal reflections.
- Heat extraction from a storage fitted with conducting fins to a cooking top plate was of acceptable efficiency for storage temperatures above 200 degrees C (1 liter water would boil in 20 minutes). Below 200 degrees better thermal contact is needed.
- A fiber mesh heat absorber at the focal point works well (40-80% efficiency) provided the concentration ratio is high enough (above 100).
- A complete system test gave about 150 degrees C storage temperature with about 30 % heat collection efficiency (concentration ratio about 25).

The system offers a low cost and simplistic solution for collection and storage of solar heat for food preparation. The fan solution (hardware and control) needs to be improved. A high concentration ratio also demands careful construction and tracking accuracy.



<b>Experimental and numerical investigations of a small scale double-reflector concentrating solar system with latent heat storage</b>	
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Foong Chee Who – 2011	
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Norwegian University of Science and Technology	Supervisors: Ole J. Nydal, J. Hustad
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### ***Objectives***

The objectives of the work are to design, construct, test and analyze a small scale concentrating system with direct illumination of a heat storage unit. The storage is to be applied for cooking purposes.

The concept is based on small heat storage units (heat batteries) providing sufficient heat for cooking one meal.

### ***Tasks***

1. Characterize Nitrate mixtures as phase change materials (PCM) for thermal energy storage ( $\text{NaNO}_3$ - $\text{KNO}_3$  mixtures. “solar salt”).
2. Design, construct and test a double-reflector concentrating solar thermal system with heat storage.
3. Validate a numerical 2D and 3D storage model by comparisons with test results
4. Perform a model based optimization of the storage
5. Construct a storage and test it for cooking applications

### ***Results***

- A double reflector system, where a secondary reflector focuses the beams onto the top of a heat storage positioned below a center hole in the primary reflector, was constructed. The parabolic dish surface was covered with a reflective film, the position of the secondary reflector determines the focusing on the storage.
- The heat capacity of solar salt was measured with a differential scanning calorimeter. This gave effective heat capacity values during the melting of the PCM, to be applied in heat transfer analysis of the storage.
- A cylindrical PCM container with conducting fins to the top plate was tested in the double reflector
- An optimized storage was constructed, based on numerical analysis (Comsol Multiphysics). The storage was successfully tested for boiling and frying on the top plate. As the storage was constructed in the winter season in Trondheim, a final charging test in the sun remains to be completed.

The concept of directly charging heat batteries has been demonstrated. Further tests will be made to quantify the heat collection efficiency and to optimize the insulation.

<b>Design, construction and experimental investigation of solar powered injera baking oven for indoor cooking</b>	
Abdulkadir Aman Hassen - 2013	
Addis-Abeba University	Supervisors: Demiss Alemu & Ole J. Nydal

### ***Objectives***

The objective of the research is to design, manufacture and study the performance of a laboratory model of a solar powered injera baking oven for indoor cooking. The system is designed as a small scale which will be integrated with a parabolic trough and heat storage for continuous making of injera as well as other foods like bread.

### ***Tasks***

- Study the thermo-physical properties of Injera and Injera baking pan analytically and experimentally.
- Investigate the performance characteristics of Electric powered Injera baking pans.
- Develop knowledge in heat transfer during Injera baking and optimize the thickness of Injera baking pan.
- Construct and investigate the performance of modified Injera baking pan
- Apply computational methods for prediction of temperature variation during Injera baking process, parameter sensitivity study and estimate parameters for power optimization during Injera baking
- Design and manufacture a laboratory model of solar powered Injera baking system.
- Perform experimental and computational study of solar powered Injera baking system.

### ***Results***

- Correlations were developed to determine the thermo-physical properties of Injera to simplify the tedious process of calculating the values for different temperature range and moisture content.
- The geometry of existing baking pan was modified and a new ceramic baking pan was manufactured in local ceramic factory. The new pan is used for oil and electric powered baking systems.
- The Laboratory model of the solar powered Injera baking pan gives acceptable heat up and baking time, still with a room for further improvement. Ash insulation was found to be perfect for our system. The quality and texture of Injera were similar to existing ones.
- Generally, the proposed solar powered Injera baking pan gives reasonable heat up, idle and baking times for 8 mm thick ceramic baking pan (verified with FEM).
- The Electric powered ceramic baking pan is also another outcome of the research work, with significant improvement in power consumption compared to existing baking pans.

<b>Design, construction and characterization of a multiple sensor, solar radiation detector</b>	
Marcelino Adriano Macome - 2014	
University of KwaZulu Natal – Durban, RSA	Supervisors: Alan Matthews, J. Løvseth

### ***Objectives***

The main objective is to develop a low-cost solar radiation detector that can be used to gather solar radiation data, the basic information required in solar resources deployment. With an aim to assist on a feasible and sustainable deployment of solar radiation resources which in turn will contribute on improving the quality of life standard of the Mozambican community by ensuring a high quality database from which the assessment of solar radiation behaviour and design of suitable solar energy systems can be based on, wherever is needed.

### ***Tasks***

- a) Design and construction of the detector;
- b) Characterization with respect to spectral and cosine responses. It will also be characterized with respect to environmental stability (e.g. thermal effect, soiling);
- c) Calibration of the detector.

### ***Results***

- Finalization of construction process and calibration of the sensors.
- Data gathering.
- Thesis preparation
- Writing paper for publication.

<b>Energy Market in Mozambique: Analysis of the current and future pathways</b>	
Gilberto Mahumane - 2014	
Eduardo Mondlane University	Supervisor: Peter Mulder, VU University Amsterdam; Co-supervisor: Boaventura Cuamba, Eduardo Mondlane University, Maputo.

### *Objectives*

The thesis aims at evaluating current and future supply and demand of energy at the sectorial level, with the view to contribute with scientific basis towards sound options for energy use in Mozambique.

### *Tasks*

1. Building comprehensive database of the Mozambican energy sector for the period 2000-2011. This includes collecting data on production, consumption, import, export and prices of various energy carriers: electricity, biomass, natural gas and other fuels, from different institutions and by means of surveys.
2. Building LEAP model scenarios for energy consumption in different sectors.

### *Results*

**a.** The energy data collection process is almost completed. A database has been constructed that includes information on production, consumption, import and export of the various energy carriers for the period 2000-2011. These data have been processed, i.e. they have been made consistent across time and sources, and checked with experts in the field.

**b.** An integrated LEAP scenario model of the Mozambican energy sector has been created. The model is based on the database of the Mozambican energy sector for the period 2000-2011 (as developed under Task 1) and various sub-models that serve scenario making. The model is running, and first results for scenarios until 2030 have been presented at the International Energy Workshop (IEW), a leading large-scale international scientific conference in the field of energy studies.

**c.** Using the LEAP scenario model a draft paper has been written under the title “Energy Outlook for Mozambique 2012-2030”. This paper has been presented at the aforementioned International Workshop, and is in preparation to be submitted to Energy Policy.

<b>A socio-spatial assessment of solar energy implementation in poor communities with KwaZulu-Natal, South Africa</b>	
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Suveshnee Munien - 2013	
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University of KwaZulu Natal – Durban, RSA	Supervisors: Urmilla Bob
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**Objectives**

Survey two areas with different population densities (Inanda and Bergville) regarding implementation of solar energy.

**Tasks**

- Conduct a needs analysis for selected poor rural communities at the household and the community level
- Examine existing energy sources and their impact
- Investigate household preferences and attitudes towards solar energy systems
- Construct a spatial analysis model in conjunction with an implementation strategy and a monitoring and evaluation scheme for the introduction of solar energy systems in poor rural communities

**Results**

Majority of respondents < 35 years, with low levels of formal education.

Alarming levels of unemployment (50-70%)

Reliant on electricity, paraffin, fuelwood (Bergville more pronounced)

Limited understanding of solar energy, however most are willing to use

Highlights the need for pro-poor technologies

Data still to be more analysed and PhD finalized

<b>Cooking with the sun - A comparative study of implementing institutional solar cookers in the developing world</b>	
Pia Otte 2013	
Norwegian University of Science and Technology	Supervisor: Jonathon Moses

### ***Objectives***

The objective of the study is to contribute to answering the following research questions:

- What are the determining factors that make public institutions adopt solar cookers?
- What are the possibilities of an institutional solar cooking system in the case of Mozambique?

### ***Tasks***

Scheffler reflectors (which are a certain type of solar cooker) are compared in different developing countries with different levels of use within and between countries. Fieldwork for conducting the data, which will be analyzed with Qualitative Comparative Analysis (QCA) was collected in the following countries and time periods:

- July-August 2011- South Africa, Botswana
- November- December 2011: India
- November- December 2012: Burkina Faso

Furthermore, for analyzing the potential of solar cooking in Mozambique, data on the energy use and needs is conducted from different public institutions (e.g., schools, hospitals, teacher training centers) in Sofala and Maputo province in Mozambique. This part of the fieldwork was undertaken in two intervals, one in April 2011 and a second one between June and August 2011. In total 24 institutions could be interviewed in those two areas.

### ***Results***

A list of 6 core variables was derived, which is considered to influence the adoption of solar cookers. In 9 out of 24 cases Scheffler reflectors are still in use. The analysis leaves us with four core variables, the presence of which leads to the successful adoption of solar cookers. These are: (1) schedule of daily routine, (2) food characteristics, (3) economic motivation and (4) environmental motivation.

An interesting result is that most of the institutions, which have adopted solar cookers successfully are religious institutions and that 'food characteristics' and 'environmental motivation' take on a new meaning in this context. The religious institutions that successfully adopted solar cookers show a very strong affinity for protecting nature as part of their spiritual belief. Furthermore, the study shows that motivational aspects can be important in ways that are not yet recognized. The traditional focus on motivation has been on its capacity to create interest in an innovation. In the case of solar cookers, motivational aspects partly determine whether an institution keeps those cookers in use continuously. (Analysis for the Mozambican part of the study is still in progress.)



## 15 MSc

<b>Improvement and performance testing of parabolic trough collector for indoor cooking</b>	
Haftom Asmelash	
University of Dar-Es-Salaam, NOMA 2011	Supervisors: Mulu Bayray Kahsay (Mekelle) Cuthbert Kimambo

### *Objectives and tasks*

- Improve the existing parabolic trough collector with the aim of:
- Increasing the temperatures to 200<sup>0</sup>C at the absorber and 100<sup>0</sup>C at the cooking pot
- Test the performance of the system

### *Results*

- Ray tracing tests showed wide scatter of rays out of focus which lead to re-installation of the trough mirrors;
- Tests conducted with fin and without fin indicated that the fin has negative effect on the efficiency;
- Test was then conducted with circulating oil which reached temperature of 126 °C at the cooking pot;
- Cooking tests were conducted with egg and potato which were cooked after 1 hour and twenty minutes.

<b>Design of solar cooker based on concentrating collector using heat transfer fluid</b>	
Petros Gebray Enday	
Makerere University, NOMA 2010	Supervisors: Mulu Bayray Kahsay, Mekelle University Adam Sebit, Makerere University

### *Objectives and tasks*

The objective of the thesis was to design and build a solar cooker based on concentrating solar collector. The cooker uses a heat transfer fluid to heat a cooking pot.

The specific objectives of this project were:

- Analyze and determine the energy demand for cooking.
- Size main features of the cookers such as the collector area, geometry, piping system and cooking enclosure
- Test the performance solar cooker

### *Results*

Maximum standard stagnation temperature of 159<sup>0</sup>C was reached.

Maximum temperature of 126<sup>0</sup>C at the absorber outlet and 86<sup>0</sup>C at the cooking pot have been achieved with natural circulation of the oil.

Maximum cooking power of 327 W was obtained and the overall efficiency was about 3%.

Significant losses were observed at the finned tube absorber and recommendations were made to further test with absorber with no fins.

<b>Investigation of heat pipes as a means of heat transfer device for solar thermal application</b>	
Ashenafi Kebedom	
Makerere University, NOMA 2010	Supervisors: Mulu Bayray Kahsay (Mekelle) Adam Sebit

*Objectives and tasks*

The objective of this research is to carry out an investigation of different heat pipe configurations as heat transfer device to reduce heat loss in the application of solar thermal systems mainly from storage to load.

The specific objectives of this project were:

- To design and construct a system used to produce heat pipes
- To investigate the effect of varying the length of heat pipes on the thermal performance of the heat pipe.
- To investigate the effect of using a wick on its thermal performance.
- To investigate the effect of inclination of the heat pipe

*Results*

A set up for producing heat pipes has been prepared,  
Experiments were conducted to see the effect of wick, slope and length of the heat pipes.

<b>Investigation on viability of solar water heating system for industrial applications in northern Ethiopia</b>	
Roble Cherkos	
Makerere University, NOMA 2010	Supervisors: Mulu Bayray Kahsay (Mekelle) Izael Pereira Da Silva

*Objectives and tasks*

The general objective of this project work was to investigate the possible use of solar energy for a large-scale water heating systems in industries.

The specific objectives of this project were:

- To predict the solar radiation data of the selected areas
- To determine the energy demand for water heating of selected industries.
- To study different types of solar water heating systems and configurations to satisfy the specific demand of each of the four factories under consideration.
- To compare the technical and economic viability of solar water heating system as a replacement for the current water heating system.

*Results*

Case studies in four industries: tannery, textile, particleboard and edible oil factories were conducted. The study found that there is very high hot water demand in tanneries and edible oil factories, medium demand in textile factory and low demand in particle board factory. The factories can save their energy cost by 26-33% by implementing the solar water heating systems.

<b>Experimental test of closed loop solar steam system of parabolic dish for injera baking</b>
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Arkbom Hailu
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Mekelle University, EnPe 2011	Supervisors: Mulu Bayray Kahsay, Asfafaw H. Tesfaw
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*Objectives and tasks*

Building manual solar tracking,  
 Construct clay plate that suit with the system,  
 Test the setup for pressurized steam generation and direct baking,  
 Evaluate the overall performance.

*Results*

A laboratory setup of two axes solar tracking was designed and constructed,  
 Daily and monthly solar tracking was practiced,  
 Steam circulation was created by the solar energy on the system,  
 A maximum of 63 °C on the clay plate was obtained.

<b>Solar autoclave for rural clinics</b>
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Habteweld Ababu
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Mekelle University, EnPe 2011	Supervisors: Mulu Bayray Kahsay, Petros Gebray
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*Objectives and tasks*

- To analyze the amount of heat required for sterilization;
- To size components of the solar autoclave (collector area, its geometry, and the pressure vessel);
- To measure the temperature and pressure parameters.

*Results*

- Solar autoclave was designed and tested using a parabolic dish collector for rural clinics application;
- Minimum sterilization temperature of 121°C and pressure of 2 bar were obtained;
- The time to reach this sterilization temperature varied from 10 to 30 minutes;
- The sterilization cycle ends with a time range of 40 up to 60 minutes with a possibility to carry out more than two sterilization cycles per day.

<b>Modelling of beam solar radiation on a horizontal surface at Makerere University</b>	
John Paul Eneku	
Makerere University	Supervisors: E. J. K. Banda and J. Mubiru

*Objectives and tasks*

1. To measure horizontal-beam solar radiation at Makerere University using an Epply Normal Incidence Pyrheliometer
2. To compare horizontal-beam solar data measured using the Kipp and Zonen CSD1 sensor with horizontal-beam solar radiation data generated by NIP
3. To determine corrective models for the CSD1 sensor for the measurement of horizontal-beam solar radiation
4. To formulate a sunshine-based empirical model for the prediction of hourly horizontal-beam solar radiation.

*Results*

It was found that CSD1 did not have the same level of accuracy as the Normal Incidence Pyrheliometer (NIP) for measurement of horizontal-beam solar radiation and its values required a correction to make up to the level of the NIP.

Empirical models have been developed, which can be used to correct hourly horizontal-beam solar radiation data measured by Kipp and Zonen sunshine duration sensor, during clear and partly-cloudy skies. A sunshine bases empirical prediction model has been developed for hourly values horizontal-beam radiation at Makerere University.

<b>Thermal properties of selected materials for thermal insulation available in Uganda</b>	
Gertrude Ayugi	
Makerere University, NUFU 2011	Supervisors: Eldad J.K. Banda, Florence D'Ujanga

*Objectives and tasks*

The objective is to investigate the thermal properties of selected insulating materials available in Uganda that can be used for thermal insulation. The tasks are to measure:

1. The thermal conductivity of selected materials available in Uganda.
2. The thermal diffusivity of selected materials available in Uganda.
3. The specific heat capacity of selected materials available in Uganda

*Results*

The use of thermal insulators is one of the most important aspects in thermal energy storage systems. This research presented investigations of thermal properties of selected materials available in Uganda which can be used for thermal insulation. Thermal properties of seven different materials were measured. The materials studied were: sugar cane fibers, ash, banana fibers, sawdust, clay, kaolin, and charcoal dust. The thermal properties investigated were, thermal conductivity, thermal diffusivity and specific heat capacity.

From the samples studied, sugarcane fibers/ bagasse was the best insulating material.

<b>Heat storage for oil based solar concentrators</b>	
Rune Herdlevær	
Norwegian University of Science and Technology NTNU 2012	Supervisors: O.J. Nydal, M. Mussard

*Objectives and tasks*

A latent heat storage (solar salt) to be charged with heated oil from a solar trough was designed, constructed and tested.

*Results*

The storage was constructed as a cylindrical container with heated oil entering from the absorber at the top and leaving back to absorber from a pipe at the bottom. Aluminum cylinders were welded to the top plate, and the cylinders were immersed down into the oil. The cylinders were open at the top and were filled with solar salt.

Charging experiments were made with electrical elements on the absorber pipe. Melting of the solar salt (about 210 degrees C) was achieved with self-circulation alone.

<b>Heat storage for vapor based solar concentrators</b>	
Catharina Hoff	
Norwegian University of Science and Technology NTNU 2012	Supervisors: O.J. Nydal, M. Mussard

*Objectives and tasks*

A latent heat storage unit (solar salt) to be charged with steam from a solar concentrator was designed, constructed and tested in the laboratory.

*Results*

The storage was made of a block of aluminum. Cylindrical cavities were drilled to contain the solar salt. Three channels were made for the steam and connected to one inlet and one outlet pipe. The steam channels were closed by welded seals.

The storage was tested in a closed loop laboratory setup. Steam was generated with electrically elements coiled around the pipe. Charging at a melting temperature of about 210 degrees require steam pressure of about 35-40 bar. Self-circulating tests were successfully made. The storage was insulated with aerogel. The temperature sank from 220 to 50 degrees C in 85 hours.

Thermal analysis was made with COMSOL Multiphysics, with a link to INVENTOR drawings.

<b>Absorber for concentrating solar heat collectors</b>	
Trygve Veslum	
Norwegian University of Science and Technology NTNU 2011	Supervisors: O. J. Nydal, H. Madessa

*Objectives and tasks*

Two types of volumetric heat absorbers for the air system have been tested: honeycomb silicon carbide and stainless steel fiber mats. A dedicated setup was made with a parabolic dish covered with reflective film and with a fan drawing air through the absorber positioned at the focus point.

*Results*

Air temperatures up to 300 degrees were measured for concentration factors of 300. Higher air flow rates give higher efficiency but lower temperatures. The efficiency in heat conversion was between 50% and 80%.

Both absorbers can be applied for air based solar thermal heat collectors. The highest temperature was measured with the honeycomb absorber: 350 degrees C at 600 concentration ratio and 0.0015 kg/s air flow rate.

<b>An investigation of the efficiency of a solar thermal cooker with thermal energy storage</b>	
Heiko Heilgendorff	
University of KwaZulu-Natal 2013	Supervisors: Dr AP Matthews, Prof Jorgen Løvseth

*Objectives and tasks*

Construction and refurbishment of an on-axis half-parabolic 2.4 m dish with reflective tiles, using a tracking program, oil as heat transfer liquid, and pebble storage. Testing of two receivers: flat coil and concave cup coil.

*Results*

System has been completed. Tracking is working, as well as oil flow. Without oil flow, receiver reaches stagnation temperature of over 400 °C. With oil flow, temperatures of well over 100 °C achieved in oil and storage. Testing is still underway, and thesis being written.



<b>Construction and optimization of the receiver for a solar thermal energy system</b>	
Paulene Govender	
University of KwaZulu-Natal 2013	Supervisors: Dr AP Matthews, Prof Jorgen Løvseth

#### *Objectives and tasks*

Construction of a system with a 1.2 m off-axis parabolic dish with tracker that uses shading of photodiodes. Dish rotates on a frame about a stationary receiver that is a cylindrical boiling chamber with a hemispherical end on which the radiation is focused. Boiling chamber contains water in a closed system of a steel pipe that loops through a storage container with copper fins in solar salt. The intention is that superheated steam at 40 atm and over 200 °C flows through the storage loop and condenses to flow back into the boiling chamber.

#### *Results*

System has been constructed and exposed to radiation. Tracking not working yet. Heating of storage not yet as planned. Temperature of 200 °C achieved in receiver. Steam produced. Still in completion and testing stage. Thesis being written.

<b>Software development &amp; analysis of parabolic trough solar electric generation system (PTSEGS)</b>	
Mekuannint Mesfin	
Addis Ababa University, NUFU	Supervisors: Dr.Ing Ababayehu Assefa

#### *Objectives and tasks*

The objective of the thesis is to design and manufacture a parabolic trough solar concentrator and development of a software for the analysis of parabolic trough solar electric generation system (PTSEGS).

- Designing and manufacturing of a parabolic trough solar concentrator
- Designing and manufacturing of a heat exchanger
- Designing of the piping system
- Designing and manufacturing of the tracking system
- Development of software for the analysis of parabolic trough solar electric generation system

#### *Results*

A parabolic trough concentrator is designed and manufactured with two-axis tracking system. In addition a user friendly software is developed for the analysis for parabolic trough solar electric generation system.

<b>Transient heat transfer analysis of injera baking pan (“Mitad”) by finite element method</b>	
Assefa Ayalew Tareke	
Addis Ababa University	Supervisors: Dr.Ing Demiss Alemu & A.A. Hassen

*Objectives and tasks*

The main objective is to develop a finite element model for injera baking pans during initial heat up and injera baking process, conduct experiments to get the parameters needed in modeling and optimizing the geometry of the baking plate based on the results obtained in the model. The tasks are:

- Develop transient two-dimensional heat transfer model of electric injera baking pans and conduct sensitivity based on geometry (thickness of pan) baking pans, thermo-physical properties of pan (density, thermal conductivity, and specific heat capacity) and the supplied heat generation source;
- Conduct transient two-dimensional heat transfer analysis in Injera during baking process.

*Results*

The conventional electric injera baking pan was studied first because of the ease of analysis. The thesis produced an initial base-line study of normal electric injera baking pan operation and energy optimization in injera baking. It also produced a relatively accurate numerical model of electric injera baking pan operation.

<b>Design and manufacture of laboratory model for indirect solar heater injera baking pan</b>	
Alehegn Mossu	
Addis Ababa University	Supervisors: Dr.Ing Demiss Alemu & A.A. Hassen

*Objectives and tasks*

The main objective of the thesis is to design and manufacture laboratory model for indirect solar heater injera baking pan that uses oil as a heat transfer fluid from the solar receiver to baking pan/mitad. The tasks are:

- Design and manufacture of components for a laboratory model of indirect solar heater injera baking setup
- Assemble components and perform experimental study.
- Recommend the type of solar collector for this type of application.

*Results*

- To bake injera using indirect solar heater system with the help of heat transfer fluid and to have pan surface temperature of 200 °C, the heat transfer fluid should be heated up to 298.4 °C for 10mm thick mitad;
- The baking pan surface temperature in the experiment was measured. The minimum temperature on the baking surface was 61 °C with nearly uniform temperature compared to electrical injera baking pan;
- Based on the required optimum oil temperature used for injera baking; a two axis tracking parabolic trough type of solar collector is recommended.

<b>Experimental investigation on performance characteristics and efficiency of electric injera baking pans (Mitad)</b>	
Awash Tekle	
Addis Ababa University	Supervisors: Dr.Ing Demiss Alemu & A.A. Hassen

*Objectives and tasks*

The main objective of the thesis work is to investigate the performance characteristics and efficiency of the electric cooking appliance ‘mitad’ (improved and conventional baking pans: clay and ceramic pans) experimentally and to identify the factors affecting the efficiency of the baking pans. The tasks are:

- Determining baking temperature and measure moisture loss of the injera batter;
- Compare the performance of the conventional and improved baking pan.

*Results*

Based on the experimental result, the moisture and solid content of the batter are 73% and 27%, and for injera it is around 58% and 42 % respectively. The experimental result shows that the maximum energy losses of conventional and improved cooking appliance ‘mitad’ occur at the bottom of the baking system by 30% and 21% with baking pan efficiency of 52% and 77% respectively. Even though the efficiency of improved baking pan is higher than the conventional baking pan, still there is high energy loss due to poor insulation

<b>Design and manufacture of a laboratory model for solar powered injera baking oven</b>	
Mekonnen Mesele	
Addis Ababa University	Supervisors: Dr.Ing Demiss Alemu & A.A. Hassen

*Objectives and tasks*

The main objective of the thesis is to design, manufacture and study the performance of a heat transport system for solar powered injera backing oven that uses oil as a heat transfer fluid from the solar receiver to baking pan. The tasks are:

- Design and manufacture an air free heat transport system loop from oil storage tank to the injera baking compartment;
- Performing a series of experiments during initial heat up and baking using the laboratory model of the system.

*Results*

The baking of injera starts after the baking pan surface temperature reaches 215°C, when the batter (locally called ‘lit’) is powered on the pan surface, the temperature of pan surface drops to about 92°C, it takes about two minutes to bake one injera and about three minutes to recover the pan surface temperature to bake another injera, that is there is about five minutes gap between each consecutive injera baking time. The baking pan surface temperature in the experiment was measured and a temperature of about 215°C was registered; which is in the range to bake injera and a nice injera was baked on this pan surface.

<b>Heat transfer analysis during the process of injera baking by finite element method</b>	
Gashaw Getnet	
Addis Ababa University	Supervisors: Dr.Ing Demiss Alemu & A.A. Hassen

### *Objectives and tasks*

The main objective of this thesis is the modeling and simulation of heat transfer in injera and baking pan during baking. A transient heat transfer mathematical model for the baking pan, and a heat and mass transfer model for injera was developed. The tasks are:

- Study geometry of the baking pan, injera, and prepare a model for the analysis.
- Conducting simulations during heat up and cyclic injera baking for different types of baking pans (clay, and ceramic), and different power sources.
- Determination of efficiency, and proposing energy efficient baking pan.

### *Results*

Simulation of baking pans for heat up time with thicknesses greater than or equal to 0.01m shows that, it is difficult to achieve surface baking temperature (200°C) using heated oil temperature of 250°C. For the conventional baking pan heated oil temperatures of 300°C and above are required to achieve surface baking temperature.

From the temperature profile of injeras baked with different power sources, it can be concluded that, the formation of proper injera requires a specific rate of initial power delivery. Too little power delivery will not properly boil the water in the batter, while too much power will create uneven boiling which may result in an improper moisture content of injera.

<b>Assessment of the Efficiency of Solar Radiation Concentrating System</b>	
Célia Artur	
University of Kwazulu – Natal 2011	Supervisors: S. R. Pillay Co-Supervisor: J. Løvseth

### *Objectives and tasks*

- Construct the concentrating system and design an optimal receiver and focal length for the prototype
- Investigate thermal efficiency of the heat system by measurements of the inlet and outlet temperatures of the oil in the absorber and the thermal storage and the temperature of the environment

An existing setup at UKZN was modified, instrumented and tested regarding heat absorption, transport and release to a storage by a circulating oil. The concentrator is a half dish, tiled with acrylic mirrors. The pump is a modified motorcycle oil pump. The absorber is a spiral tube mounted at the bottom of a heating pot.

### *Results*

The tests showed that the system can work, provided a pump control is in place. Overheating of the oil must be avoided, and the pump power will depend on the

temperature of the oil, as the viscosity reduces with increasing temperature. The efficiency of the system was about 35 %.

<b>Social and economic impact of the use of photovoltaic systems in the district of Moamba-Pessene</b>	
Alina AMC Bungueia	
Eduardo Mondlane University, Maputo, Mozambique NORGLOBAL 2014	Supervisors: Vasco Nhabinde, Boa Cuamba and Gilda Monjane

*Objectives and tasks*

- Environmental implications that the use of these systems has for the environment
- Attempt to estimate potential saving from the use of renewable energies

*Results*

The study started in late 2013 and will complete in February 2014

<b>ANALYSIS OF RENEWABLE ENERGY POLICY: A Contribution to Economic Development of Mozambique</b>	
Mery Mondlane	
Eduardo Mondlane University, Maputo, Mozambique NORGLOBAL 2014	Supervisors: Vasco Nhabinde, Boa Cuamba and Gilda Monjane

*Objectives and tasks*

- Assess the contribution of renewable energy policy for the economic development of Mozambique
- Evaluate the policy on renewable energy and their impact (effect) on economic development
- Identify investment in sources of renewable energy and their effect on rural development
- Analyze the impact of renewable energy on poverty in rural areas
- Attempt do estimate potential saving from the use of renewable energies

*Results*

The study started in late 2013 and will complete in February 2014

<b>The role of photovoltaic energy for promotion of sustainable development: case study of two rural communities of Mozambique (Djabula and Tinonganine)</b>	
Gilda Monjane	
Eduardo Mondlane University, Mozambique, NORGLOBAL 2012	Supervisors: Gerhard Liesegang

*Objectives:*

The main objective of the dissertation is to discuss the role of Photovoltaic Energy in promoting sustainable development in rural villages of Mozambique.

- Characterization of the socio-cultural, demographic and economic situation of the place of Study;
- Check the expansion of freedom of making choice made by people that may be resulting from the use of photovoltaic energy;
- Identification of the limitation that the installed Photovoltaic system may have;
- Compare the implementation of the photovoltaic electrification programs in Tinonganine and Djabula;
- Description of the influence that photovoltaic energy may have in promoting equality, equity and gender empowerment.

*Sample and Guiding Theory:*

The sample of the study consisted of 104 elements, among them 52 women and 52 men, each of them representing a household. The theoretical approach is based on a triangulation of Amartya Sen (1999), who looks at development as freedom, completed by Brundtland (1987), who emphasizes the importance of sustainability in development actions, and Durkheim's functionalist theory that conceives a society as composed of different parts that complement each other in order to maintain its structure.

Through the combination of the three theories we found support for the study of the social dimension of access to photovoltaic energy, in the process of reproduction of social relations.

*Results*

The results of the study indicate that photovoltaic energy could serve as a lever to promote sustainable development of rural communities, eliminating barriers socially embedded and constructed through the relationships between individuals, particularly regarding to gender relations. However, the development of the studied community did not reach the expected level due to several factors, such as, the destruction of the photovoltaic systems, existence of few beneficiaries, poor management associated with lack of inclusion of a social component during planning process for the intervention, combined with absence of an ideal structure that fits the context for marketing, supply and maintenance of the photovoltaic systems.

Another outcome of the project is that the completion of the master degree gave Gilda Monjane the opportunity to be employed at the Ministry of Energy in Mozambique. The main work area is on gender concerns in the Energy Policy and Strategy



## 16 Dissemination

### Publications and conferences

2012 M. Mussard, A. Gueno, O.J. Nydal Experimental study of solar cooking using heat storage in comparison with direct heating. Energy conversion and management (submitted).

2012 M. Mussard, O.J. Nydal Charging of a heat storage coupled with a low cost small-scale parabolic trough for cooking purposes. Solar energy (submitted).

2012 M. Mussard, O.J. Nydal Influence of solar tracking inaccuracy on the efficiency of a small-scale parabolic trough. Optics and laser technology (submitted).

2012 M. Mussard, O.J. Nydal Comparison of oil and aluminum-based heat storage charging coupled with a small-scale solar parabolic trough. Applied thermal engineering (submitted).

2012 M. Mussard, E. Vaujany, O.J. Nydal Heating of an oil-based heat storage with a low-cost small-scale solar parabolic trough. Proceedings of the Eurosun conference 2012, Opatija, 18-20 Sept. 2012, Croatia.

2012 M. Mussard, O.J. Nydal Assessments of the thermal storage potential of sensible and latent heat-based systems for solar domestic applications. Proceedings of the IRES conference 2012, Berlin, 12-14 Nov. 2012, Germany.

2011 M. Bayray, R. Cherkos, I. Pereira Da Silva Investigation of Solar Water Heating Systems for Industrial Applications in Northern Ethiopia. Proceedings of the ISES Solar World Congress 2011, Kassel, 28 Aug – 2 Sept. 2011, Germany

2011 A. Kebedom, M. Bayray, A.M. Sebbit Investigation of Heat Pipes as a Means of Heat Transfer Device for Solar Thermal Applications. Proceedings of the ISES Solar World Congress 2011, Kassel, 28 Aug – 2 Sept. 2011, Germany

2011 P. Gebray, M. Bayray, A.M. Sebbit Design of Solar Cooker Based on Concentrating Collector Using Heat Transfer Fluid. Proceedings of the ISES Solar World Congress 2011, Kassel, 28 Aug – 2 Sept. 2011, Germany

2011 Abdulkadir A. Aman, Demiss A. Amibe, O.J. Nydal Performance Investigation of Solar Powered Injera Baking Oven for Indoor Cooking Proceedings of the ISES Solar World Congress 2011, Kassel, 28 Aug – 2 Sept. 2011, Germany

2011 Bayera, H, J. Løvseth and Nydal, O.J Performance analysis of finned type rock bed used as a heat storage unit and a cooking device. Proceedings of the ISES Solar World Congress 2011, Kassel, 28 Aug – 2 Sept. 2011, Germany

2011 Bayera, H, Veslum T., J. Løvseth and Nydal, O.J Investigation of a solar absorber for small scale solar concentrating parabolic dish. Proceedings of the ISES Solar World Congress 2011, Kassel, 28 Aug – 2 Sept. 2011, Germany

- 2011 Bayera, H, Chee Woh Foong, Nydal, O.J Ray tracing for analysis of concentrated sun rays through a channel. Proceedings of the 40<sup>th</sup> ASES National Solar Conference , North Carolina, US. 2011
- 2011 Denis Okello, Chee Woh Foong, E.J.K.B. Banda, Ole Jorgen Nydal An experimental investigation on the combined use of phase change material and rock particles for high temperature (350 degrees C) heat storage. Proceedings of the ISES Solar World Congress 2011, Kassel, 28 Aug – 2 Sept. 2011, Germany
- 2011 Foong, C.W., J. Løvseth and Nydal, O.J., Experiments on heat extraction from a latent heat storage unit with NaNO<sub>3</sub> - KNO<sub>3</sub> medium. Applied Thermal Engineering (submitted).
- 2011 Foong, C.W., J. Løvseth and Nydal, O.J., Parametric analysis of a latent heat storage unit with NaNO<sub>3</sub> and KNO<sub>3</sub> phase change material. Applied Thermal Engineering (submitted).
- 2011 Foong, C.W., J. Løvseth and Nydal, O.J., Investigation of a small scale double- reflector solar concentrating system with high temperature heat storage, Applied Thermal Engineering. Volume 31, Issue 10, July 2011, Pages 1807-1815
- 2011 Foong, C.W., J. Løvseth and Nydal, O.J. 3-dimensional finite element analysis of a latent heat storage unit with NaNO<sub>3</sub> and KNO<sub>3</sub> binary mixture. Proceedings of the 40<sup>th</sup> ASES National Solar Conference , North Carolina, US. 2011
- 2011 Foong, C.W., J. Løvseth and Nydal, O.J., Heat capacity measurement of NaNO<sub>3</sub> – KNO<sub>3</sub> binary mixture, International Journal of Thermophysics. (Submitted).
- 2011 G.Ayugi, E.J.K.Banda, F.M.D’ujanga Local Insulating materials for Thermal Energy Storage, Rwanda Journal Series C23, 21-29 (2011).
- 2010 Foong, C.W., Hustad, J.E., Jørgen, L. and Nydal, O.J., 2010, Numerical study of a high temperature latent heat storage (200-300<sup>0</sup>C) using NaNO<sub>3</sub> – KNO<sub>3</sub> binary mixture, *Proceedings of the 6th annual COMSOL Conference*, Paris, France.
- 2010 Foong Chee Woh, H. Madessa, O. J. Nydal Development of a solar concentrator with heat storage. Proceedings of 4th International Solar Energy Society Conference, Asia Pacific Region, Yokohama, Japan 27 june–2 july, 2010
- 2010 Foong Chee Woh, J. Hustad, O. J. Nydal Investigation of thermophysical properties of high temperature latent heat storage material NaNO<sub>2</sub> Proceedings of 4th International Solar Energy Society Conference, Asia Pacific Region, Yokohama, Japan 27 june–2 july, 2010
- 2010 Foong Chee Woh, J. Hustad, O. J. Nydal Investigation of a high temperature thermal energy storage (200-300<sup>0</sup>C) using eutectic salts of sodium nitrate and potassium nitrate. Proceedings of 4th International Solar Energy Society Conference, Asia Pacific Region, Yokohama, Japan 27 june–2 july, 2010
- 2010 Habtamu B. Madessa, Ole J.Nydal, Jørgen Løvseth Tracking System Directly Controlled By Solar Panels Int conf.: Renewable Energy Beyond 2020, Trondheim, Norway, June 7th - 8th 2010

- 2010 Habtamu B. Madessa, Ole J.Nydal, Fong Chee Who, Jørgen Løvseth Ray Tracing for Analysis of Concentrating Solar Systems Proceedings for the ASME-ATI-UIT 2010 Conference on Thermal and Environmental Issues in Energy Systems, 16 – 19 May, 2010, Sorrento, Italy
- 2009 Habtamu B. Madessa, Jørgen Løvseth, Ole J.Nydal Experimental investigation on rock bed for high temperature solar thermal storage... ISES Solar World Congress, Johannesburg, 12-14 October 2009
- 2009 D. Okello, E.J.K.B Banda, J.Løvseth, O.J.Nydal Temperature Profile in rockbed heat storage for food preparation... ISES Solar World Congress, Johannesburg, 12-14 October 2009
- 2009 K. Nyeinga, E.J.K.B. Banda, O.J.Nydal, J.Løvseth Dynamic model for small scale concentrating solar energy system with heat storage... ISES Solar World Congress, Johannesburg, 12-14 October 2009
- 2009 Actor Chikukwa, Jørgen Løvseth Modeling of a novel volumetric absorber, suitable for compact solar concentrator with rock storage... ISES Solar World Congress, Johannesburg, 12-14 October 2009
- 2009 D Actor Chikukwa, Jørgen Løvseth Optimization and modeling of a high temperature solar storage adapted for hot plate operation... ISES Solar World Congress, Johannesburg, 12-14 October 2009
- 2009 G. Doho and K. Govender Microcontroller Based Data Acquisition and Control of a Solar Thermal Energy System ISES Solar World Congress, Johannesburg, 12-14 October 2009
- 2009 Mulu Bayray Solar water Heater Employing Heat pipe ISES Solar World Congress, Johannesburg, 12-14 October 2009
- 2009 B. C. Cuamba, M. L. Chenene, J. Lovseth, O. Nydal and B. Karlsson The Role of research, education and training in promoting the deployment of renewable energy in Mozambique. ISES Solar World Congress, Johannesburg, 12-14 October 2009
- 2009 C. Artur, B. Cuamba, S. Pillay and J. Lovseth Assessment of the Efficiency of a Solar Radiation Concentrating System ISES Solar World Congress, Johannesburg, 12-14 October 2009
- 2009 B. C. Cuamba, M. L. Chenene, A. R. Domingos, J. Lovseth, O. J. Nydal Design and construction of a sun tracker for use in low cost small scale multipurpose thermal solar energy concentrating systems. 10th world renewable energy congress - WREC X
- 2009 M A Macome, B. Cuamba, S. Pillay and J. Lovseth Design, Construction and Characterization of a Multiple Sensors Solar Radiation detector ISES Solar World Congress, Johannesburg, 12-14 October 2009
- 2008 J.Mubiru and E.J.K.Banda Applicability of Various Diffuse Radiation Models at an equatorial African site Discovery and Innovation Publication Vol.20 No.1,14-19,2008
- 2008 J.Mubiru, E.J.K.B.Banda Estimation of monthly average daily global solar irradiation using artificial neural networks Solar Energy 82 (2008)181-187

2007 M A Macome, J S P Mlatho, M McPherson The response of a silicon diode designed for use as a detector for direct solar radiation IOP Publishing, Measurement Science and Technology 2007

2007 B. C. Cuamba, M. L. Chenene and V.V. Tchernych Energy Sector Activities in Mozambique: Present Status and Future Prospects ISSN 1607-8829 Journal of Thermoelectricity No4, 2007

### **Reports and project notes**

2012 Ball Receiver Project note Jorgen Løvseth

2012 Off axis system overview Project note Jorgen Løvseth

2012 Cast aluminium hot plate Project note Jorgen Løvseth

2012 50 cm solar metad Project note Jorgen Løvseth

2012 50 cm solar salt storage Project note Jorgen Løvseth

2012 Rotating off-axis dish Project note Jorgen Løvseth

2012 Offset dish metad Project note Jorgen Løvseth

2012 Metad 60 cm for casting

2011 Improving heat transfer in a pressurised boiling system by steel pipes imbedded in aluminium. Project note Jorgen Løvseth, Project note Jorgen Løvseth

2011 Description of a new support system for the Maputo dish. Project note Jorgen Løvseth

2011 Off axis system. Project note Jorgen Løvseth

2011 Control unit for oil flow between storage and receiver of concentrating solar oven. Project note Jorgen Løvseth

2011 Solar salt storage with thermal stratification. Project note Jorgen Løvseth

2011 Test rig for metad heated by water thermosyphon. Project note Jorgen Løvseth

2011 Solar tracking accuracy How it affects size of the concentrated image in the focal plane. Project note Jorgen Løvseth

2011 Interception studies with ray tracer. Project note O. J. Nydal

2011 Receiver and oil transport system for Celia solar system. Project note Jorgen Løvseth

2011 Receiver for air based solar oven planned at EMU. Project note Jorgen Løvseth

2010 October Note on self circulation water-trough system with a small storage and hotplate.  
Jørgen Løvseth

2010 10 November Use of EPT solar simulator lamps Project note Jørgen Løvseth

2010 May Konsentrerende solfanger med varmelager M. Karlsen, S.Skarra, S.O. Edvardsen  
Sluttrappor for avsluttende BSc prosjekt ved HIST

2010 31 May Rock storage conductivity. Project note Jorgen Løvseth

2010 16 April Insulation by evacuation. Project note Jorgen Løvseth

2009 Project report "Experts in team" project group Teknologi kløften: Kan solkokerteknologi  
overføres med suksess ?

2009 Project report "Experts in team" project group Teknologi kløften: En  
implementeringssuksess for solovnen

2009 Habtamu Bayera Participation on Norwegian Research council FORNOY-program at  
NTNU and winning of the 'stipendordningen 2009'

2009 February Two Phase heat transfer fluid. Project note Jorgen Løvseth

### **Student reports**

2009 Svein Ivar Malde, Atle Meistad, Joakim Rygg Flesvik, Lasse Moksnes Weie Styring av  
solfanger. Sluttrappor for avsluttende BSc prosjekt ved HIST

2010 Kontrollsystem for konsentrerende solfanger med varmelager Marius Karlsen, Sigurd  
Skarra, Svern Ove Edvardsen Sluttrappor for avsluttende BSc prosjekt ved HIST

2011 To-akset styring av solkonsentrator Ellen Stølen, Karianne Biørn, Liv Marit Hustad,  
Mads Aas and Vegard Storm. Sluttrappor for avsluttende BSc prosjekt ved HIST

2010 Design and further development of a solar oven intended for use in the global south.  
Arnstein Johannes Syltern MSc Industrial Design

2010 Absorber for concentrating solar heat collectors Trygve Veslum Student project report

2011 Solar energy: Insulation methods for a heat storage Marie Seltveit Haugen Student project  
report

2011 Analysis of a heat storage for solar energy Carlos Perez dela Blanca Castellano Student  
project report

2011 Solar tracking methods for small scale concentrating systems Guillaume.Lerouge Student  
project report

2011 Solar energy: assessment of a directly heated storage unit Rune Herdlevær og Cecilie Kvangarsnes Student project report

2012 Off-set solar reflectors for heat collection Harald Andreassen and Victoria Sivertsen

2012 Ray tracing for solar system analysis on GPU Stian Aaraas Pedersen (collaboration with IDI)

### **Presentations**

2012 Rock bed for heat storage: experiments and modeling. Lecture Dar Es Salaam Univ. August 8, 2012 O.J. Nydal

2012 Solar Energy Network Project. Presentation EnPe seminar, Dar Es Salaam Univ. August 9, 2012 O.J. Nydal

2012 Ray tracer analysis of reflection systems. Lecture Dar Es Salaam Univ. August 8, 2012 O.J. Nydal

2012 Experiences with a rock bed for heat storage. Lecture Mekelle Univ. May 7, 2012 O.J. Nydal

2012 Ray tracing algorithms. Lecture Mekelle Univ. May 7, 2012 O.J. Nydal

2011 Commercial concentrating solar power systems Lecture Mekelle Univ. May 23, 2011 Jorgen Løvseth

2011 Rock bed for heat storage. Lecture Mekelle Univ. May 24, 2011. O.J. Nydal

2011 Ray tracing for solar reflection systems. Lecture Mekelle Univ. May 24, 2011. O.J. Nydal

2011 Network project on small scale concentrating solar energy systems Meeting with Ministry of Water and Energy, Addis Ababa, Ethiopia. 19 September 2011, O.J. Nydal

2011 NUFU Network Project: Small Scale Concentrating Solar Energy Norad-SIU seminar 27 Jan 2011 O. J. Nydal

2010 30 March Lecture on HTF properties. Jorgen Løvseth

2009 10-12 September, Ole Jorgen Nydal, Small scale solar energy system Renewable Energy Seminar, University of Dar Es Salaam, Tanzania

2011 Experiences from a regional NUFU Network project on solar energy. SIU-Norad seminar Dar Es Salaam 16 Nov. 2011. O. J. Nydal

2012 Exhibition of solar project, Forskningstorget Oslo, Forskningsrådets telt 21-22 September 2012

2012 Project presentation at NABA East Africa Seminar, Trondheim, 8 March 2012



2012 Visit to Norwegian Embassy during Solar seminar, Maputo, Mozambique, 1 May 2012

2011 SIU Internet Magazine: Highlights. Social Aspects of Solar Energy 2 May 2011

<http://www.siu.no/eng/Front-Page/Highlights>

2010 8 August 12 foreign journalists laboratory visit

2010 18 March 30 politicians Finland and Sweden laboratory visit

2010 15 March Laboratory visit solar oven: Norwegian Church Aid Mali

2009 1 October: Schrødingers katt, NRK TV

2009 24 September Ren og billig energi fra solovn, Adresseavisen, Trondheim

2009 25-26 September Exhibition: Utstilling solovn Forskningsdagene. Trondheim Torg,

2009 June, YouTube, [www.youtube.com/watch?v=EhvgCdedn\\_I&feature=player\\_embedded](http://www.youtube.com/watch?v=EhvgCdedn_I&feature=player_embedded)

2009 24 March, Energi til Afrika, Byavisa Trondheim

2009 11 March, 12:30 Innslag i P2 radioprogrammet Verdt å vite

2009 10 March, Solenergi mot sult, Under Dusken(Studentavisa I Trondheim)

2009 03 March, Fanger Sol till kveldsmaten, Stavanger Aftenblad

2009 Februar, Fanger Sol till kveldsmaten GEMINI (Forskningsnyheter fra NTNU og SINTEF)

## **Workshops**

Yearly project meetings

2007 NUFU Network Workshop hosted by Eduardo Mondlane University, Maputo, 15-16 June

2008 NUFU Network Workshop hosted by Makerere University, 18-19 September

2009 hosted by CSIR, Pretoria, and UkZN, Durban in connection with ISES Int. Solar Conference in Johannesburg, South Africa, 15 October

2010 NUFU Network Workshop hosted by Addis Ababa University, Addis Ababa, 25-27 September

2011 NUFU Network Workshop arranged in connection with ISES conference in Kassel, 29 August 2011

2012 NUFU Network Final Seminar, Trondheim, 8-9 October 2012

**Visitors to NTNU solar laboratory****2012**

Oluwatosin Ajayi	Summerjob double reflector system
Alexandre Gueno	Internship from Poitier University, France. Trough system test
Parakram Pyakurel	Visiting EnPe student from Nepal University (6 months)
Shanti Prajapati	Visiting EnPe student from Nepal University (6 months)
Abdulkadir Aman	Visiting PhD thesis writing (2 months, Addis Aaba)
Denis Okelle	Visiting PhD Network Project (1 month, Makerere Univ., rock bed)
Karidewa Nyeinga	Visiting PhD Network Project (1 month, Makerere Univ., simulation)

**2011**

Ellen Stølen	BSc thesis on two axis solar tracking
Karianne Biørn	BSc thesis on two axis solar tracking
Liv Marit Hustad	BSc thesis on two axis solar tracking
Mads Aas	BSc thesis on two axis solar tracking
Vegard Storm	BSc thesis on two axis solar tracking
Carlos Castellano	Visiting MSc on steam charged PCM storage
Guillaumet Lerouge	Visiting project student on single axis simplified solar tracker
Amos Veremachi	Visiting PhD on air absorber construction
Abdulkadir	Visiting PhD on steam circulation loop

**2010**

Marius Karlsen	BSc thesis (HIST, solar tracking and fan control)
Sven Ove Edvardsen	BSc thesis (HIST, solar tracking and fan control)
Sigurd Skarra	BSc thesis (HIST, solar tracking and fan control)
Rolf	Vacuum insulation consultant (Vakum teknologi)
Helene Billond Grand	Visiting student (6 months, Polytech Marseille)
Remi Picard	Visiting student (3 months, Poitier, france)
Tor Kjeldby	Summer job (Sterling engine)
Denis Okelle	Visiting PhD Network Project (1 month, Makerere Univ., rock bed)
Karidewa Nyeinga	Visiting PhD Network Project (1 month, Makerere Univ., simulation)

**2009**

David Fischer	Summerjob double reflector setup
Aberra	Summerjob double reflector setup
Svein Ivar Malde B	BSc thesis (HIST, solar tracking and fan control)
Atle Meistad	BSc thesis (HIST, solar tracking and fan control)
Joakim Rygg Fleksvik	BSc thesis (HIST, solar tracking and fan control)
Lasse Moksness Weie	BSc thesis (HIST, solar tracking and fan control)

**Presentations from the social science side**

2013 Pia Otte “Warming up to solar cooking-A comparative study on motivations and the adoption of institutional solar cookers in the developing world”, (oral presentation) ISES Solar World Congress 2013, Cancun, 3-7<sup>th</sup> of November, Mexico.

2013 Pia Otte, “What I learned from cooking with the sun” TEDx talk Trondheim salon event “Re-thinking Green”:

- 2013 Pia Otte “Warming up to solar cooking-A comparative study on motivations and the adoption of institutional solar cookers in the developing world”, (oral presentation) ISES Solar World Congress 2013, Cancun, 3-7<sup>th</sup> of November, Mexico.
- 2013 Pia Otte, “What I learned from cooking with the sun” TEDx talk Trondheim salon event “Re-thinking Green”:
- 2012 Pia Otte “The impact of spiritual commitment on the social adoption of institutional solar cooking - The case of the Brahma Kumaris” Poster presentation, Eurosun conference 2012, Rijeka 18.- 20. Sept. 2012, Croatia
- 2012 Pia Otte ” Solar cooking a solution looking for a problem? Rogers` Innovation Decision-Process in the context of institutional solar cooking in Mozambique” (oral presentation) Post COP 17 Climate Change and Livelihoods in Africa, 9-15<sup>th</sup> of July 2012, University of Botswana
- 2011 Pia Otte Overview PhD project “Cooking with the sun- A comparative analysis of implementing solar cookers in the developing world” NORGLOBAL Dissemination Seminar, Oral presentation 25 October 2011, Oslo
- 2011 Pia Otte “Using the sun`s power to cook- An interdisciplinary project for the development & implementation of a solar cooking system in Africa” NORGLOBAL Dissemination Seminar , Poster presentation: 25 October 2011, Oslo
- 2011 Pia Otte “Small scale concentrating solar energy systems: Technical development and social adoption” Presentation at workshop: International Co-operation in Science, Technology and Innovation to address global challenges- Food, water, energy and community, Trondheim, 5 October 2011
- 2011 Pia Otte “What makes public institutions applying a solar cooking system? The case of Mozambique” Presentation at NUFU network project annual meeting, Kassel, Germany September 2, 2011
- 2011 Pia Otte “Limits and possibilities of institutional solar cooking in Mozambique” Proceedings of the ISES Solar World Congress 2011, Kassel, 28 Aug – 2 Sept. 2011, Germany