Low cost thermal storage for solar dryers in the Himalayas

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LUND UNIVERSITY

Thesis for the degree of Master of Science

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Abstract

Post-harvest losses in the himalayan regions of Nepal and Bhutan are high, and current drying methods are in need of improvement. This report improves on a previously developed solar dryer design and evaluates thermal storage solutions for the 'SolarFood: Reducing post-harvest losses through improved solar drying' project. This report uses experimental measurements to compare different dryer configurations, as well as results from previous measurements and experiments to improve the current prototype. The report studies two different solar dryer prototypes located at Kathmandu University based on the same design. Previous hypotheses regarding leakage in the solar dryer prototype were partly solved. Incorporating a thermal storage system utilizing water as the working material can increase control over the solar dryer and increase consistency. The system presented is low-cost and performs adequately. The system is adaptable to different temperature ranges and requirements and should be applicable for use with different drying commodities. Previous studies have utilized rocks or gravel as the working material. A comparison measurement in this report shows water performs favorably toward rocks or gravel.

Notations

Notation	Physical quantity	Unit
a_m	fraction melted	
Δh_m	heat of fusion per mass	J/kg
C_{sp}	average specific heat in interval T_{min} to T_{melt}	J/kgK
C_{lp}	average specific heat in interval T_{melt} to T_{max}	J/kgK
C_p	specific heat	J/kgK
T_{melt}	melting temperature	˚C
T_{min}	minimum required temperature temperature	˚C
T_{max}	maximum temperature	˚C
m	mass	kg
Q	stored heat	J
C	heat capacity rate ($C_p \frac{dm}{dt}$)	J/kgK $\frac{dm}{dt}$

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1 Project Introduction & Background

1.1 Project introduction

This report is part of 'SolarFood: Reducing post-harvest losses through improved solar drying'. The project is aiming to develop locally adapted solar dryers to reduce post-harvest losses in the Himalayan regions of Nepal and Bhutan. [1] This report will perform research and experiments on a low cost thermal energy storage solution for use in the solar dryer concept previously developed within the project.

1.2 Aim

This report aims to investigate different alternatives of storing heat in a previously developed solar dryer concept by measurements on the laboratory prototype at Kathmandu University. [2] The report also aims to improve the leakage issues and improve overall performance of a second prototype solar dryer with incorporated heat exchanger at Kathmandu University. [3]

1.3 Economics

GDP/capita (nominal) for Nepal was 900 USD in 2017. Can be compared to Sweden (54 075 USD) or Bhutan (3 391 USD). With purchasing power (PPP) taken into account to adjust for cost of living, Nepal trails with 2 702 USD compared to Sweden's 51 405 USD or Bhutan's 9 392 USD [4]. Thus, keeping costs down for the solar dryer is vital for the success of this project. Expensive or complex solutions have to be weighed carefully in comparison towards performance benefits.

1.4 Solar drying technology

Drying food is necessary to solve the issues that farmers currently face. Dried food will last longer without spoiling, and may be easier to package and ship due to the weight reductions that come with reduced water content. A controlled drying process is necessary to increase quality and consistency. Drying temperatures are usually in the range of 45 °C to 60 °C for fruits and vegetables. Keeping temperatures within an acceptable range for drying is important to avoid microbial growth, preserve nutrients while maintaining an adequate drying rate. [5]

Open air sun drying

Currently, small-scale farms in Nepal mainly utilize open sun drying. As there is neither an enclosure nor any efficiency measures taken, this causes risk of contamination from insects, pests etc. Drying rates are also poor, as well as controllability. The necessity to dry products over a time period spanning multiple days causes additional fluctuations in moisture content. The quality of the final product is poor. [6] [7] [8]

Direct solar dryer

Direct solar dryers are inexpensive and simple. The dryer utilizes a single-chamber design housing the absorber and the drying chamber. This dryer type faces issues such as relatively low capacity and poor performance. Capacity and performance issues enhance each other, as the issue stems from the fact that commodities can only be placed in one layer. As the absorber area is covered with a drying commodity, the potential absorbed solar energy is reduced. In addition, direct exposure to solar radiation can cause quality degradation, such as discoloration and loss of vitamins, for the dried commodity. [8] [9]

Indirect solar dryer

The indirect solar dryer splits the absorber and the drying chamber into two separate volumes. This dryer type achieves higher performance while still keeping cost relatively low. By nature, this dryer does not expose the commodities to solar radiation.[8]

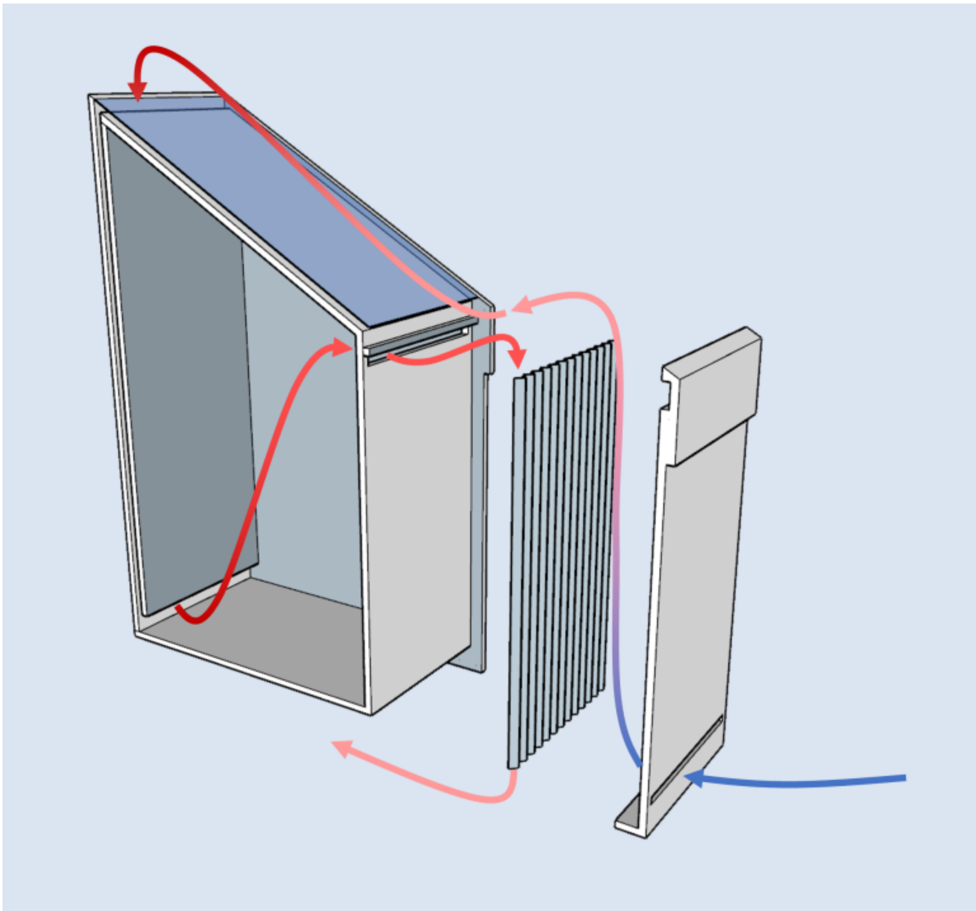

Figure 1: The existing solar dryer concept [3] (used with permission from Adam Probert)

Figure 1 shows the indirect solar dryer concept used as a starting point for this project. The solar dryer in question features an incorporated heat exchanger to improve thermal efficiency and raise temperatures inside the dryer. The heat exchanger in question is a simple design using bent sheet metal. Heat losses from leaks are present and the construction is in need of improvement. [3] A prototype of this concept has been constructed on a rooftop at Kathmandu University. Construction details can be seen in the report by Probert. [3]

A second prototype with similar geometry but without a heat exchanger has also been constructed in a laboratory at Kathmandu University. Construction details can be seen in the report by Karlsson Faudot. [2] This prototype has a significantly smaller volume and was constructed for research on effects of air flow and different fan configurations. The prototype has no incorporated heat exchanger, no diffuser plate and no absorber plate. This is due to the fact that this prototype is heated from the inside of the drying chamber utilizing heat lamps.

1.5 Drying of commodities

Moisture content

Table 1 shows initial and final moisture content as well as maximum allowed drying temperature T_{max} for selected crops. Different moisture contents will lead to varying drying rates. [10] As such, a flexible system is required to allow for drying different commodities optimally with the same solar dryer.

Crop	Moisture, initial /%w.b.	Moisture, final /%w.b.	$T_{max}/^oC$
Apple	80	24	70
Apricot	85	18	65
Bananas	80	15	70
Brinjal	95	6	60
Cabbage	80	4	55
Carrots	70	5	75
Cauliflower	80	6	65
Corn	24	14	50
Garlic	80	4	55
Grapes	80	15-20	70
Green beans	70	5	75
Green peas	80	5	65
Guavas	80	7	65
Maize	35	15	60
Okra	80	20	65
Onion	80	4	55
Pineapple	80	10	65
Potatoes	75	13	75
Rice	24	11	50
Sweet potato	75	7	75
Wheat	20	16	45

Table 1: Moisture content and allowed temperature for selected crops

Drying rate and quality

Interviews with apple farmers in Nepal mention the color as an important quality indicator. [2] Rasooli Sharabiani et al. performed tests on effects on color after drying for fresh, processed food. In their testing, apple samples were dried using a microwave. As the temperature of the drying process increased, the color change increased due to increased oxidation. All tests were performed using air velocity of 1 m/s. Samples were dried at 50 °C, 60 °C and 70 °C, with the color change being the lowest at 50 °C and highest at 70 °C. Furthermore testing showed that an increase from a drying temperature of 50 °C to 70 °C causes a decrease in process time and energy consumption. The total time to dry apple slices was 200 minutes at 50 °C, 150 minutes at 60 °C and 100 minutes at 70 °C. [11] Further drying rate curve modelling can be found for open air sun drying applications for grapes, apricots, peaches, figs and plums. [12] Apples have been used for testing in previous projects utilizing the same prototype which will be used in this report.

Loss of vitamin A and C, flavonoids and polyphenols has been reported to be higher with open air sun drying compared to solar drying. Open air sun drying has been documented to cause increased loss of trans- β -carotene in product compared to utilizing a solar dryer setup. [13]

1.6 Thermal Heat Storage

The need for storing heat in solar dryer systems comes from the fact that the sun does not provide sufficient energy for drying during all hours of the day. Storing the heat produced during peak hours from the dryer and using it after sunset will yield a more even drying process and increase consistency. [5] If the dryer is able to achieve temperatures higher than what is allowed for a given fruit or vegetable, heat storage can be used to control the temperature. [14] Furthermore, the drying rate of a solar dryer can be increased by utilizing a heat storage system. [15] Thermal energy storage can be divided into sensible or latent heat storage. [5]

Sensible heat storage

$$Q = \int mC_p dT = mC_p(T_{max} - T_{min}) \tag{1}$$

Equation 1 shows heat stored in a material that does not undergo a phase change within the operating temperature range. [5] The minimum temperature T_{min} will be $T_{DC,min}$, which is defined as the minimum air temperature required for the dryer to adequately dry the commodities placed inside it. This may vary depending on the fruit or crop that is being dried, as well as air flow rates and turbulence for different dryer configurations.

Latent heat storage

Latent heat storage is described by L.M. Bal et al. as "the heat absorption or release when a storage material undergoes a change of phase from solid to liquid or liquid to gas or vice versa at more or less constant temperature [...]". [5]

$$Q = \int m[C_{sp}(T_{melt} - T_{min}) + a_m \Delta h_m + C_{lp}(T_{max} - T_{melt})] \tag{2}$$

[5]

Equation 2 shows heat stored in a material that undergoes a phase change within the operating temperature. [5] Similarly as for sensible heat storage, the minimum temperature will be $T_{DC,min}$.

Data

Material	$C_{p,solid}$ /(J/kgK)	$C_{p,liquid}$ /(J/kgK)	Δh_m	T_{melt}
C23-24(H)	2900 [16]	2130 [16]	170000	45
C31-33(H)	2900	2130	232000 [14]	68 [14]
C23-24(L)	2140 [16]	2130 [16]	170000 [14]	48 [14]
C31-33(L)	2140	2130	232000	70
Water	4184 [17]			
Granite	790 [18]			

Table 2: Data for selected materials

Table 2 shows data necessary for calculating heat storage potential. The litterature shows paraffin types C23-24 and C31-33 have a range of specific heat values. In this report, the maximum and minimum values for this range were chosen, noted with (H) for high and (L) for low. [16] [14]

Heat storage

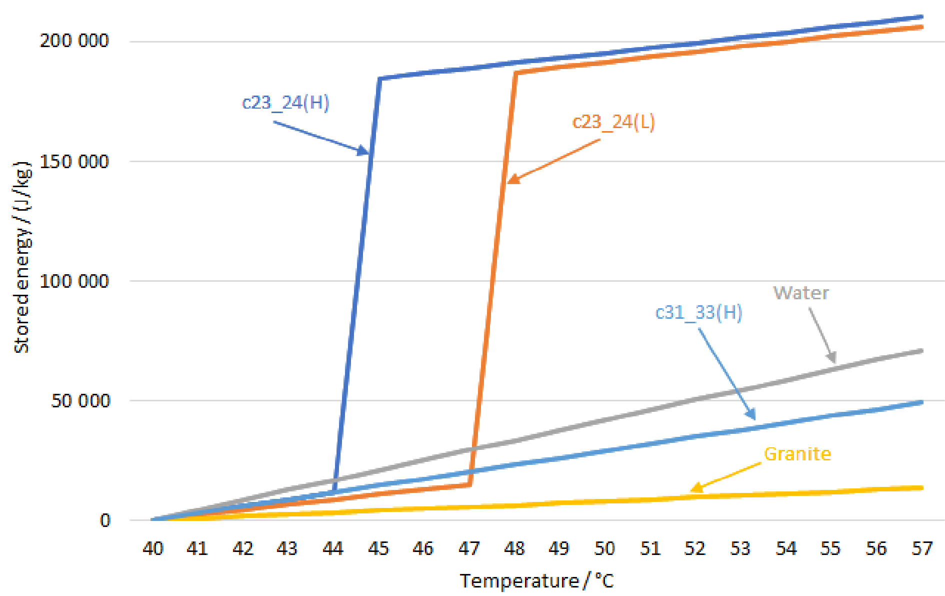

Figure 2: An illustration of latent and sensible heat storage

Figure 2 shows an illustration of sensible versus latent heat storage plotted between 40 °C and 57 °C. This is an illustrative example and does not affect the results of this report.

- The maximum temperature for the dryer is below the melting temperature for the C31-C33 paraffin wax. Thus, the C31-C33 wax will not absorb any latent heat (as it does not undergo any phase change) leading to low total stored heat values.

- C23-24 paraffin wax outperforms other selected materials if the melting point is reached. However, if the dryer does not maintain temperatures above $T_{DC,min}$ with this heat storage solution the effectiveness of the heat storage implementation is reduced. If so, a paraffin wax with a higher melting point should be used.

- Water stores more heat per kg than rock or similar materials. Sand has specific heat values similar to that of granite ($C_{p,sand} = 796$ J/kgK as compared to $C_{p,granite} = 790$ J/kgK [16]) and would thus perform poorly.

1.7 Material selection

Rocks and stones

Experiments have been performed utilizing granite spheres a heat storage material in a rock bed located after the intake but before the drying chamber in a solar dryer. Three sphere diameters were tested: 50 mm, 70 mm and 90 mm, with equal total mass. With an initial temperature of 90 °C all of the granite sphere configurations maintained a temperature of above 40 °C for more than 2 hours, which was deemed to be an acceptable minimum temperature for drying chilies. 50 mm and 70 mm spheres performed similarly, and maintained a higher temperature for longer as compared to 90 mm spheres. [19] Experiments in a tunnel dryer showed an implementation of rock bed storage increased the drying efficiency by an estimated 2 % - 3 %. [20] Garg et al. used rocks of approx. 3 cm - 5 cm in diameter contained in an iron box with air required to pass through before reaching the drying chamber. It was found that a rock bed that was too thin reduced effectiveness of the system, as the heat would pass through unabsorbed. A rock bed too thick would cause most of the heat to be absorbed on the top of the rock bed, and the thickness would cause air presssure drops. The rock bed effectively reduced the useful temperature difference in experimental testing.[21]

Phase Changing Materials (PCM)

Swami et al. tested different thermal energy storage solutions for drying fish in a solar dryer. It was found that paraffin wax of type C-31 performed worse than without any PCM. Paraffin wax of type C-23 performs better than no thermal energy storage solution. Paraffin wax C-23 has a lower melting point of 45 °C compared to 67 °C for C-31. 67 °C was above the operating temperature of the dryer, thus no phase change took place and C-31 only absorbed sensible heat. Using C-23, the drying time required by the fish was reduced by 70 % compared to open air sun drying and 20 % compared to a solar dryer without heat storage. [14]

Zinc nitrate hexahydrate has been identified as a candidate material for use in solar dryers. It has a low melting point and relatively large latent and volumetric heat of fusion. It has approximately double the volumetric energy density of paraffin. [15]

Water

Water has been identified as a possible working material choice for this project. It is low cost, high availability and has better theoretical performance than rocks or stones. It is easier to source than viable PCM's. Water "appears to be the best SHS material" because of low cost and high specific heat, but testing is limited. [22]

Water directly in contact with the air inside the dryer would risk causing changes in humidity and as such introduce additional uncertainty and complexity to the drying process. This is mitigated by storing the water in plastic bottles. The bottles are easily available and will prevent leaks, and allows for increased flexibility of positioning inside the dryer.

1.8 Heat transfer

Heat transfer comes in three forms: conduction, convection and radiation. Conduction is the heat transfer across a stationary medium with an existing temperature gradient. Convection is the heat transfer between a moving fluid and a surface when these are at different temperatures. Radiation describes heat transfer between surfaces from electromagnetic waves. [23] This report does not further elaborate on heat transfer mechanics. A brief overview of the process for the measurements goes as follows: the air will conduct heat onto the exterior wall of the plastic bottle. Heat will conduct within the thin plastic bottle wall, and convect to the water inside the plasic bottle. The process is reversed when the temperature of the water is higher than the temperature of the air outside the plastic bottle.

2 Methodology for heat storage testing

Measurements were taken using a Campbell CR1000 logger. The laboratory setup used the logger in a standalone setup. The rooftop dryer used the logger connected to a Campbell AM16/32B multiplexer.

The measuring interval was set to 30 seconds, and the log output to 1 minute. This results in an average of two measurements being recorded every minute.

Two different solar dryer setups were tested. A solar dryer in an indoors laboratory, and a solar dryer outside on a rooftop. For each setup, a baseline result was assessed. For the laboratory dryer, different configurations of heat storage were tested. 10 kg of water, 20 kg of water and 20 kg of stones.

A Testo 435-4 anemometer was used to measure the air flow at the inlet (rooftop dryer)/outlet (laboratory dryer) according to accepted methodology. [24]

The measurements were processed with regards to local air pressure and canal shape correction as described further by Karlsson Faudot [2].

2.1 Laboratory dryer

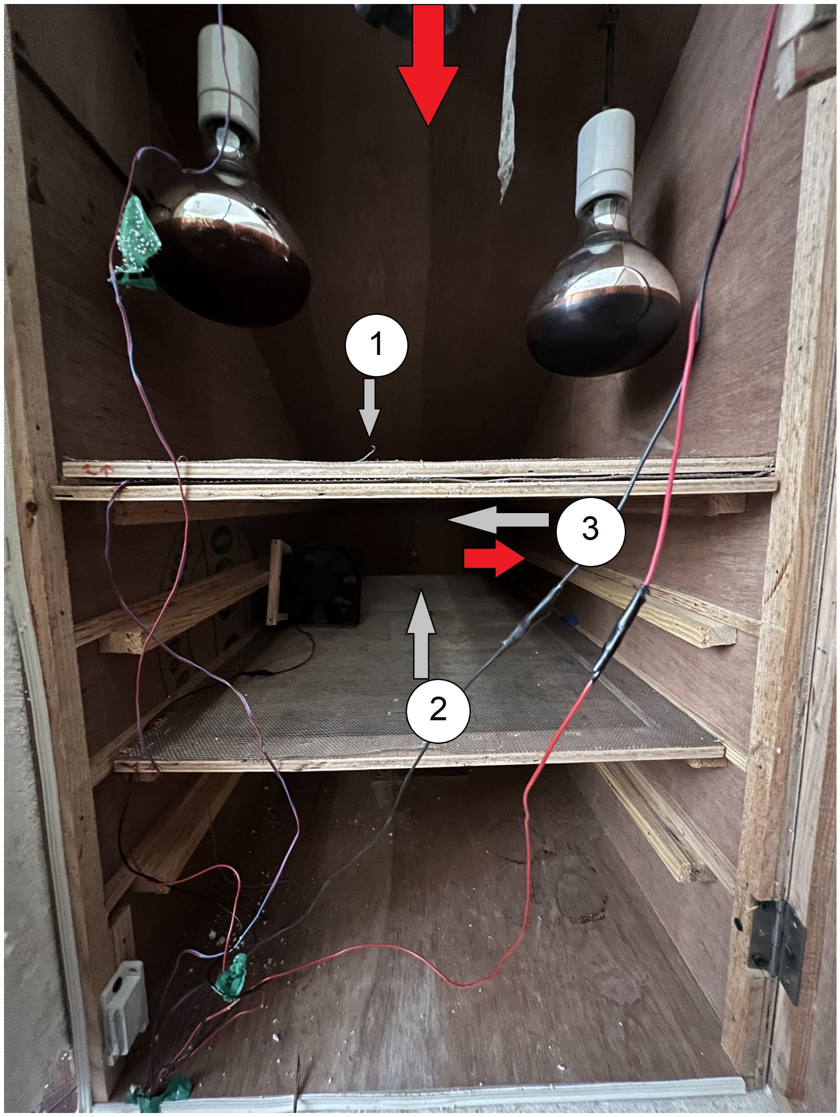

Figure 3: The laboratory dryer setup

The laboratory dryer setup is shown in figure 3. Air is pulled by the inlet fan from the red arrow at the top of the figure in the front of the dryer, and exhausted by an outlet fan by the right facing red arrow at the back of the dryer. Thermocouples 1 and 2 are placed at the middle of the drying sheets, only differing in vertical placement. Thermocouple 3 is placed at the back of the dryer to monitor any temperature irregularities. The fan seen in the left part of the figure blows air towards the back of the dryer. The heat storage configuration was placed on the floor of the dryer

Heat storage was added in the form of water inside 1 l plastic bottles. 20 bottles in total were filled up. Thermocouples were placed inside 2 bottles to measure the temperature of the water. Depending on the wanted heat storage mass, 10 or 20 bottles were placed at the bottom of the drying chamber corresponding to 10 kg and 20 kg respectively. The stored energy, Q, was calculated for the different heat storage configurations using equation 1.

For a comparison measurement, 20 kg of small pebbles and gravel were collected and placed inside the dryer. During this test, the heat storage solution utilizing water bottles was taken out of the dryer. This test is selected to provide a weight-by-weight comparison to the water systems (compared to the 20 liters of water). It is also an approximation of a volumetric comparison, since the density of water is roughly half of that of pebbles [25].

The laboratory solar dryer prototype was tested with the inlet fan, circulation fan and outlet fan all set to 5 V as well as 7,5 V and 10 V for selected measurements. The air speed and air flow is shown in table 3.

Two heating lamps of 250 W each were used to attempt to imitate the solar irradiation throughout the day. A schedule was followed for the measurements to ensure consistency:

9:15	Lamp 1 on
11:00	Lamp 2 on
14:00	Lamp 2 off
15:45	Lamp 1 off

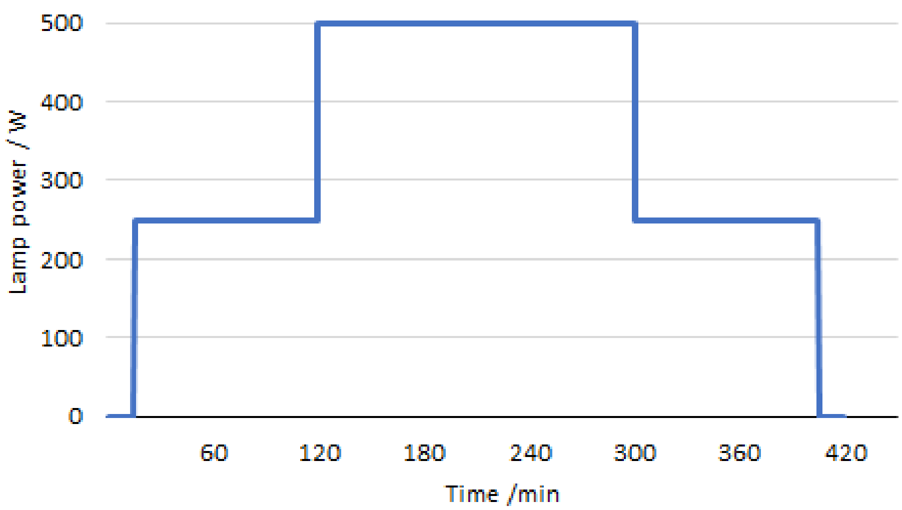

Figure 4: Heating lamp output

The schedule results in a heat lamp output illustrated in figure 4. 500 W of maximum output was chosen for attempting to mimic the solar irradiation of the rooftop dryer concept. The rooftop dryer has approximately 0,5 m^2 absorber plate. With a solar irradiation of 1000 W/m^2 this results in 500 W of possible absorbed irradiation.

Fan voltage /V	Air speed /(m/s)	Air flow /(l/s)
5	0,90	7,07
7,5	1,49	11,73
10	1,96	15,41

Table 3: Fan voltage correlations with speed and air flow

The flow was measured at the exit pipe, results shown in table 3.

2.2 Rooftop dryer

Figure 5: Exterior of rooftop dryer with new rubber strap installation

Previous research and measurements performed using the rooftop dryer prototype came to the conclusion that leakage issues were prominent. The leaks was hypothesized to originate from the door [3]. Foam tape was installed to the perimeter of the door. Rubber straps were installed to increase closing pressure of the door, as shown in figure 5

Initial measurements were carried out to get a baseline result for dryer performance. In addition to thermocouples, the rooftop dryer was equipped with a pyranometer to measure the solar irradiation.

Flow losses for the rooftop dryer were calculated using the temperature data collected before and after the heat exchange on the cold side as well as the warm side. If the temperature delta on the hot side is bigger than the delta on the cold side, this indicates a volumetric flow loss.

$$1 - \frac{\Delta T_{cold}}{\Delta T_{hot}} = flow\ loss \tag{3}$$

Where ΔT_{cold} is the temperature difference of the air from the inlet to before the absorber plate, and ΔT_{hot} is the temperature difference of the air from after the drying chamber to the outlet. Equation 3 is used to estimate the losses in air flow from leaks in the construction. This estimation is used as it is not feasible to measure the airflow at the outlet in the same manner as at the inlet for this solar dryer prototype. Do note that this is an estimation, as the air will expand as it heats up which is not taken into consideration. This expansion is proportional to the air temperature measured in Kelvin, and will as such be relatively small in this case.

The effectiveness ϵ of a heat exchanger is defined as:

$$\epsilon = \frac{C_h(t_{h_{in}} - t_{h_{out}})}{C_{min}(t_{h_{in}} - t_{c_{in}})} \tag{4}$$

Where t_h and t_c are temperatures for hot and cold side respectively, and C is heat capacity rate. With $C_h = C_{min}$ the effectiveness can be calculated.

After initial measurements, the rooftop solar dryer prototype was tested with the inlet fan set to 12 V and 5 V. This corresponds to an inlet air flow of 24 l/s and 10 l/s respectively. The 5 V-system was tested with two heat storage setups: 11 liters of water and 18 liters of water. This water was distributed in water bottles and placed inside the drying chamber, after the diffuser plate.

3 Results of measurements

3.1 Laboratory dryer

All results presented are utilizing water as the working heat storage material unless stated otherwise (figure 10 utilizes stones and pebbles). The drying chamber temperature for different configurations is presented in figures below.

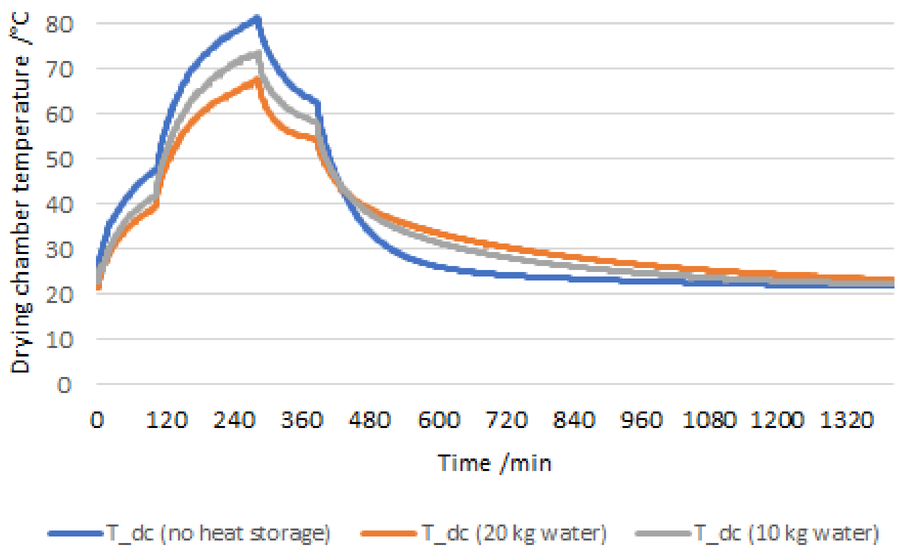

Figure 6: Results for different levels of heat storage

Figure 6 shows results for three different levels of heat storage in the laboratory dryer. T_dc0 is using no heat storage, T_dc10 is with 10 kg of water, and T_dc20 is with 20 kg of water.

One of the main reasons behind using heat storage is to reduce high temperatures considered to be too high for drying inside the drying chamber to avoid previously mentioned quality degradation issues. To visualize the effect of time spent in different temperature ranges depending on the heat storage configuration see figure 7 below.

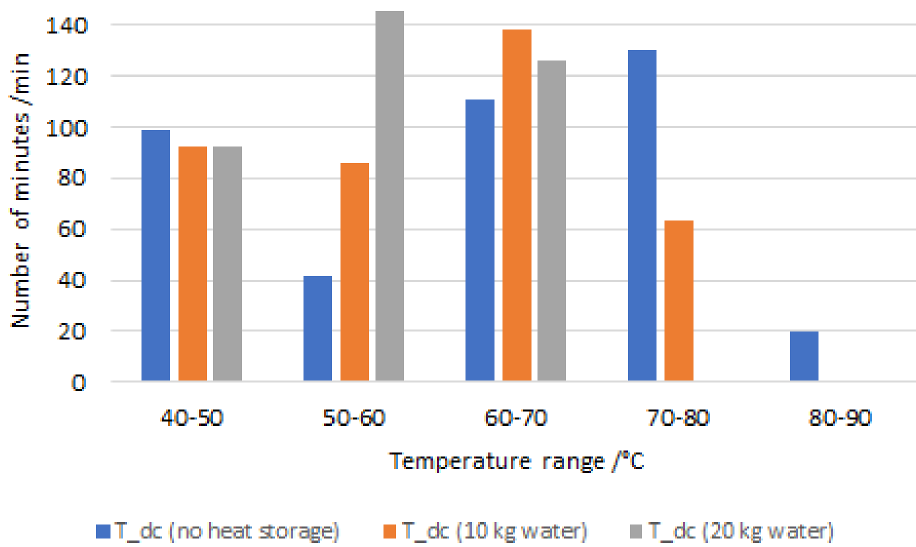

Figure 7: Histogram showing number of minutes spent in different temperature intervals

Figure 7 shows minutes spent in the intervals of 40 °C - 50 °C, 50 °C - 60 °C, 60 °C - 70 °C and 80 °C - 90 °C for different amounts of heat storage configured for use with the solar dryer. Same notations as for figure 6 apply.

From this histogram, the total amount of minutes spent within 40 °C - 60 °C were calculated. Using no heat storage, 141 minutes within the range was achieved. With 10 kg of water, 178 minutes were achieved. Finally, with 20 kg of water, 237 minutes within the range was achieved.

To compare the effectiveness of different heat storage configurations, the total energy stored in the heat storage system, Q, is calculated.

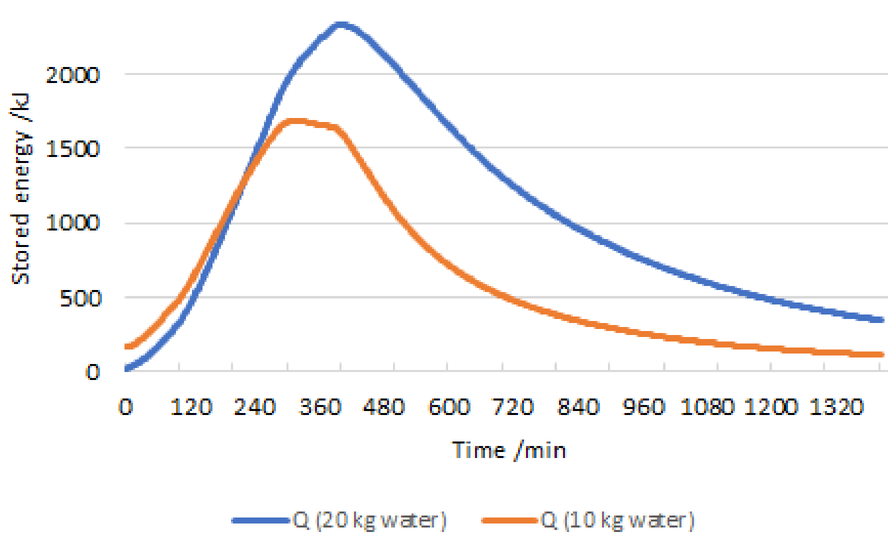

Figure 8: Total stored energy Q in the two different heat storage setups

Figure 8 shows the stored energy Q for the two different setups (10 kg and 20 kg of water). Note that the combined stored energy for all bottles combined for the system with 20 kg of heat storage is not doubled when compared to the 10 kg system. This is because the water temperature for the 10 kg system is higher, as shown in figure 9.

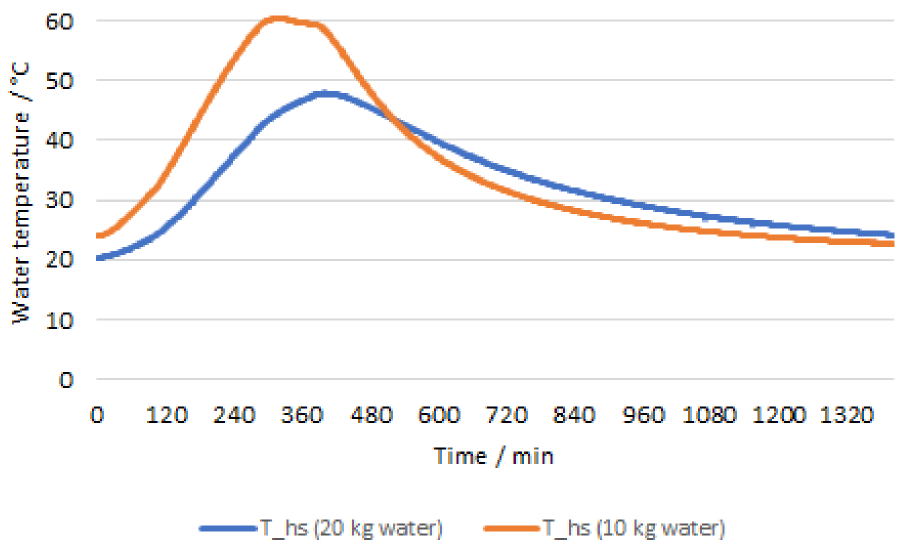

Figure 9: Average heat storage temperature for the two different heat storage setups

Figure 9 shows the average water temperature for the two different heat storage setups.

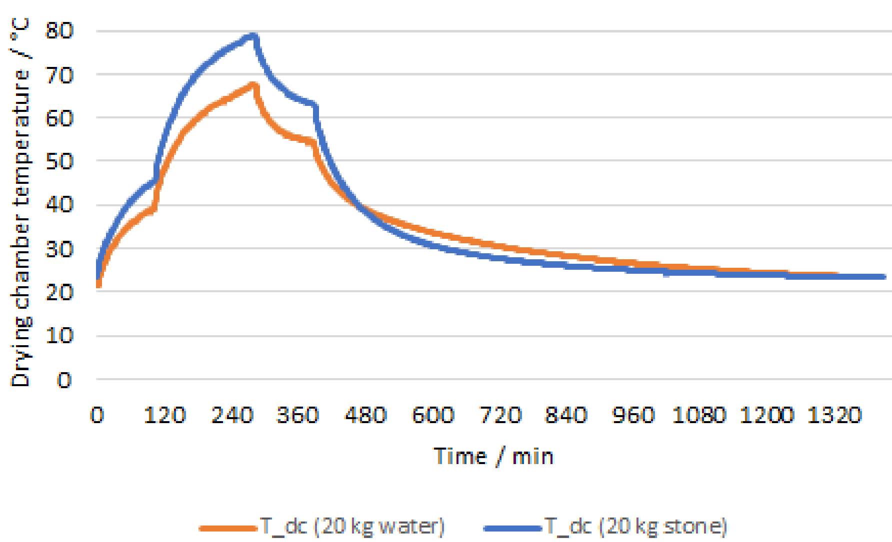

Figure 10: Drying chamber temperature comparison for water and stones

Figure 10 shows the drying chamber temperature when the dryer is configured with 20 kg mixed rocks and pebbles as the heat storage material as compared to 20 kg of water. The maximum drying chamber temperature is 79,0 °C using the stone setup.

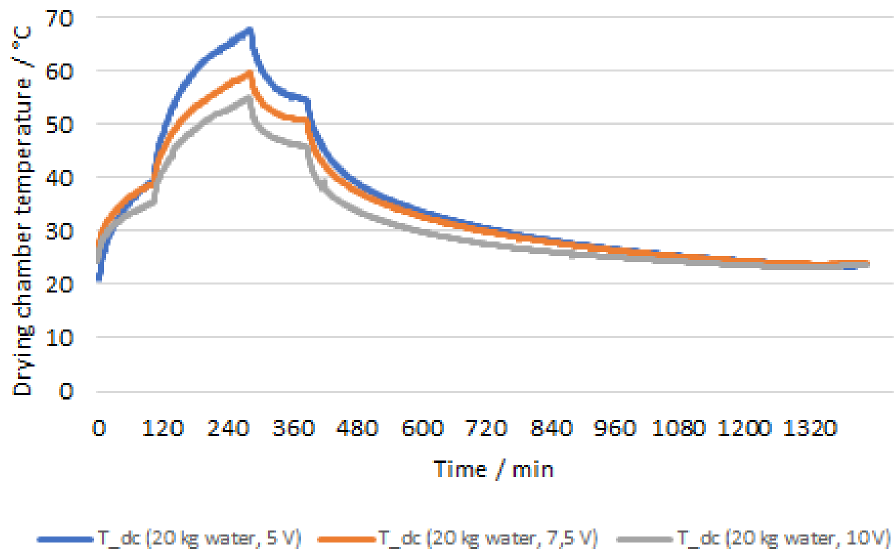

Figure 11: Drying chamber temperature depending on air speed

Figure 11 shows the drying chamber temperature for three different fan voltages (5 V, 7,5 V and 10 V) corresponding to three different air speeds and flow rates in the setup.

3.2 Rooftop dryer

All measurements for the rooftop dryer are presented without utilizing any heat storage.

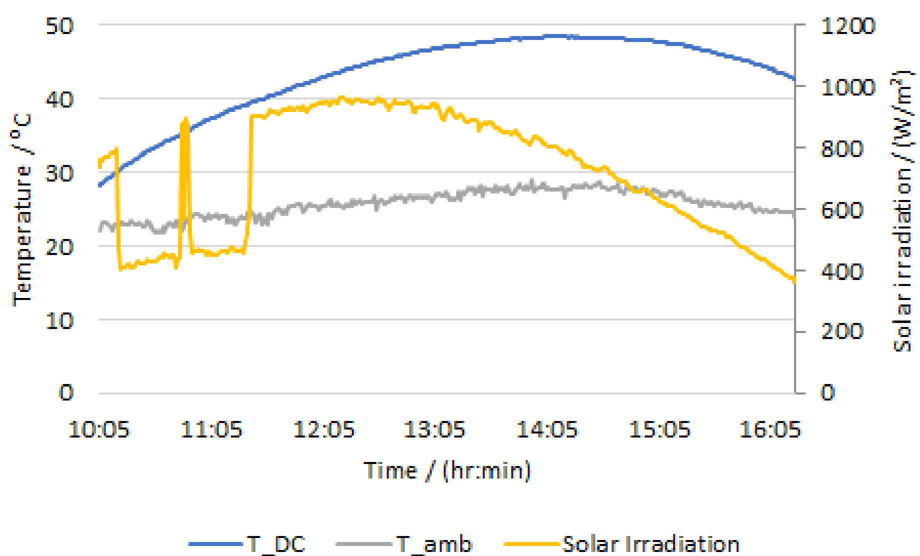

Figure 12: Baseline results for the 24 l/s configuration

Figure 12 shows baseline measurements for the rooftop solar dryer. These measurements were performed with the fan speed set to 12 V corresponding to 24 l/s. Note the partially incorrect values from the anenometer before 12:00, these should follow the curve for the afternoon. A maximum drying chamber temperature of 48,5 °C was achieved. Maximum irradiation was 965 W/m^2.

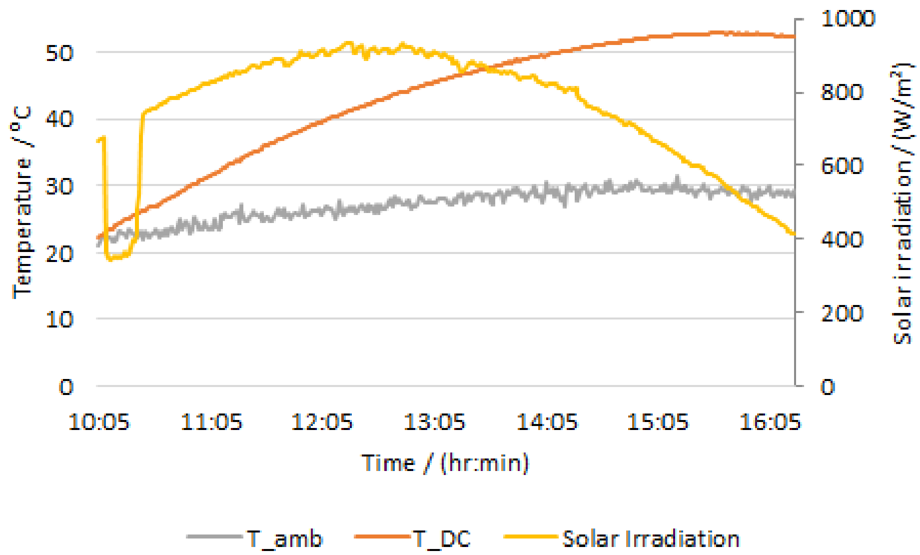

Figure 13: Baseline results for the 10 l/s configuration

Figure 13 shows baseline measurements for the 5 V or 10 l/s setup. This setup achieves a maximum drying chamber temperature of 52,8 °C. Maximum irradiation was 937 W/m^2. Similar partially incorrect values for irradiation can be noted here.

The presumed leakage for the rooftop solar dryer prototype was calculated with equation 3.

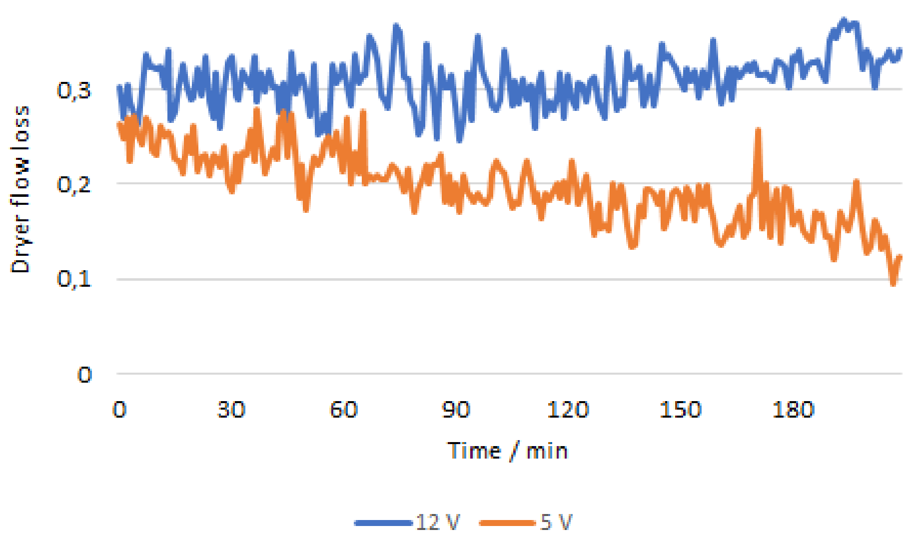

Figure 14: Flow losses for 5 V and 12 V configurations

Figure 14 shows the estimated volumetric flow losses for 5 V (10 l/s) and 12 V (24 l/s) dryer configurations. The average flow loss from 12:48 until 16:18 was 19,7 % for the 10 l/s setup and 30,9 % for the 24 l/s setup.

The effectiveness ϵ was calculated using equation 4.

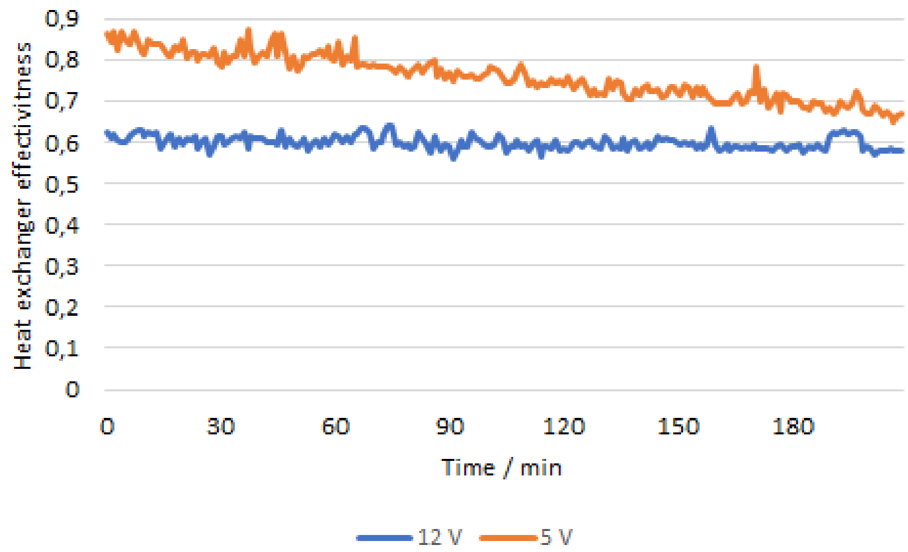

Figure 15: Effectiveness ϵ for 5 V and 12 V configurations

Figure 15 shows the effectiveness ϵ for the 5 V (10 l/s) and 12 V (24 l/s) configurations. The average effectiveness from 12:48 until 16:18 was 75,9 % for the 10 l/s setup and 59,9 % for the 24 l/s setup.

4 Conclusions

Rooftop dryer

The issue regarding a relatively large temperature gradient from the exit of the absorber plate until the entry into the drying chamber (described in previous projects as a heat lock) is still present after sealing the door. This issue is more prevalent with lower flow rates. Flow losses were reduced with the door seal implemented in this report. If the solar dryer is able to be sealed to a greater extent to further reduce flow losses, the effectiveness of the heat exchanger and overall performance would improve. The measurements conducted are not sufficient to conclude where the leaks still remaining are present. The dryer is able to be constructed locally with local materials and achieve temperatures above 50 °C in the drying chamber. After further improvements to the construction, the heat exchanger can effectiveness can be increased.

Laboratory dryer

Utilizing water inside plastic bottles as the material for a heat storage solution in the laboratory prototype has yielded a performant, flexible and inexpensive setup. Considering the varying levels of moisture content and drying rates for different products, it is key for small scale farmers to have a flexible system to allow for drying of different commodities within the same dryer. The heat storage solution presented in this report achieves that, by adding or removing water bottles depending on the commodity that is to be dried.

By adjusting how many bottles of water that are placed inside the solar dryer, peak termperatures reached inside the drying chamber can be tweaked to achieve optimal levels on a fruit by fruit or season-by-season basis.

In addition to this, using the heat storage solution presented in this report will achieve more even temperatures inside the drying chamber throughout the day, compensating for clouds or solar irradiation variances. This is shown in the results section when a lamp is turned off, the reduction in drying chamber temperature is slower with increased levels of heat storage (see figure 6).

For effectively reducing the maximum temperature achieved in the solar dryer, water performed better than rocks on a per kg basis as well as on a roughly estimated per volume basis. Rocks did achieve the desired effect of increased temperature inside the drying chamber after the heating of the dryer was turned off.

Regulating the air flow inside the drying chamber has a similar effect to regulating the heat storage configuration.

5 Reflections

An unknown issue present with the measuring setup caused issues and data corruption. Measurements using the logger may differ slightly from actual real world data. A different logger was sent for calibration but did not arrive before the departure to Nepal and could as such not be used during the first weeks of measurements. The anemometer measurements were not compensated for the air density in Dhulikhel at the time of measurements. This causes a deviation in air speed and subsequently air flow. The precise difference is unknown, but estimated to be in the range of 5 % - 20 %.

5.1 Rooftop dryer issues

Due to multiplexer malfunctions after initial measurements, data collected after malfunctions was corrupted. For the dataset including heat storage performance to be usable, it required processing and could not be deemed as accurate or reliable as the laboratory data collected. As such, it was ignored. Due to delays in shipping for a new multiplexer, further measurements were not conducted.

Outdoor measurements result in more variables to consider, such as fluctuations in irradiation, ambient temperature, wind speed and wind direction. These parameters were all considered to contribute to an increased level of uncertainty and, as such, the project pivoted to laboratory measurements.

The dryer had to be moved to a different part of the roof after approximately 4 weeks of measurements due to construction work. This may impact future measurements, it is an extra variable introduced to a complex problem.

5.2 Improvements and shortcomings for measurements on the laboratory dryer

More heating lamps with lower wattage allow achieving a smoother curve throughout the day. However, only 2 lamp holders were available in the laboratory and the author of this report was unable to source any additional holders on-site in Nepal. In addition to this, electrical outlets with timers would enable easier measurements as well as allow for more hours of measurements each day - the laboratory was only open between 9 AM and 4 PM. The thermocouples were not separated from direct line of sight of the heating lamps. It is possible that this causes undesireable heat transfer from radiation. To see if this would affect measurements, a thermocouple could be placed close to one of the positions presented in this report but somewhere which would be unaffected by radiation from the heat lamps.

6 Future work

6.1 Variable fan speed

The heat storage solutions that were studied during this project did solve the issue of a too high drying chamber temperature. Analyzing previous projects under SolarFood using the same prototypes as in this project, the author of this report notes that higher air flow also results in a lower drying chamber temperature. Air flow is controlled by regulating fan speeds. As such, it is proposed that a fan control system is investigated. This system could vary the air flow with the drying chamber temperature, increasing the flow when the temperature is high and decreasing it when the temperature is low. This could help aiding thermal heat storage systems in achieving a more even drying temperature for longer periods throughout the day. An introduction and visualization of this idea can be seen in figure 11.

6.2 Material choice

A further investigation of the viability of PCM's (for example Zinc nitrate hexahydrate) for this project would allow for the possibility of an improved drying process and increased control of said process. This investigation should include not only the material properties and performance, but also economic viability. In this report, testing of PCM's were ignored due to sourcing issues as well as being a more expensive material than water. However, this could possibly be mitigated at scale.

Rocks showed some redeeming qualities of not reducing the maximum temperatures achieved by as much as water did, while still allowing for increaed temperatures after the heat addition was stopped. The rocks available locally were dirty and dusty. This could introduce a risk of spoilage or reduce the final quality of the commodity dried inside the dryer. As such, it is recommended that viability of rocks is researched with regards to this.

6.3 Heat absorption from walls

There is a possibility that the walls surrounding the dryer chamber are absorbing some of the heat that could otherwise be used to increase the temperature in the drying chamber. This was not taken into consideration in this report. For a better overall system understanding, this should be investigated. Temperature measurements inside the insulation surrounding the dryer could help improve understanding of the mechanisms at play. This hypothesis comes from some heat exchanger calculations and measurements regarding flow loss and effectiveness not stabilizing throughout the day, as can be seen in figures 14 and 15.

6.4 Leakage issues

The rooftop solar dryer still has leaks leading to flow losses. These leaks could potentially be located utilizing smoke inside the drying chamber to visualize the flow that is lost.

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