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Solar powered paper drying in Bangladesh

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1. INTRODUCTION – ENERGY BUILDS THE NATION

In the last decades, the Bangladeshi industry has developed a lot, but there is still a lot to improve. For these improvements to continue more energy is needed, and thus a chance to focus on a sustainable energy production from the start. If not – they will have to pay twice to redesign their energy infrastructure again in the future.

Bangladesh is currently very dependent on fossil fuels for its electricity production. The main fuel used is natural gas, but the cost of gas is increasing and so is the fraction of the gas that is imported to the country. Thus the cost of producing electricity with natural gas is also increasing.

Another important fuel in Bangladesh is biomass (mainly for cooking and small scale industries), but biomass has already been exploited beyond what is sustainable and new renewable energy sources need to be established in the country.

To get a background of the possibilities available, the usability of some of the other renewable technologies is discussed, and especially the possibility to use solar thermal energy in Bangladesh is described. Finally a short comparison with the solar resource in Germany is made.

1.1 SCOPE OF THIS THESIS

All nations need energy to grow their economy and create new jobs. This study has looked at the possibility to use a solar thermal system to produce heat for small to medium scale industrial applications in Bangladesh. The research questions are explained in more details in chapter, 2 Handmade paper – a tool to create a better future but can be summarized as:

1. What is the useful heat output from an evacuated tube solar collector, operated under typical conditions in Bangladesh?
2. How big part of the heat produced can be converted into useful heat to dry papers?
3. Which of the following parameters are most important to estimate the energy needed to dry a paper?
    a. Water content in the paper
    b. The fiber used in the paper
    c. Temperature of the drier

1.2 DEVELOPMENT IN BANGLADESH

In many developing countries health has improved a lot and children are getting a better education. Bangladesh is a good example of this. In 1971 when Bangladesh gained its independence from Pakistan, in average every woman gave birth to about 7 children, but out of these about 23 % died before they turned 5 years old. In 2003 the same figures were 2.9 children per woman and only 6.9 % died before they turned 5 years old (Rosling, 2007). But during the same time the population increased from

71 million people to about 150 million people (IEA, 2011). With an area of only 147,570 km^2 (about one third of the area of Sweden) this makes Bangladesh the most densely populated country in the world (not counting city-states such as Singapore and other countries smaller than 1500 square km). On top of that Bangladesh is still one of the world's poorest countries with a GDP per capita in 2012 of only 818 USD. This is comparable with countries like Cambodia, Myanmar (Burma) and Rwanda (IMF, 2010), as can be seen in Figure 1 below.

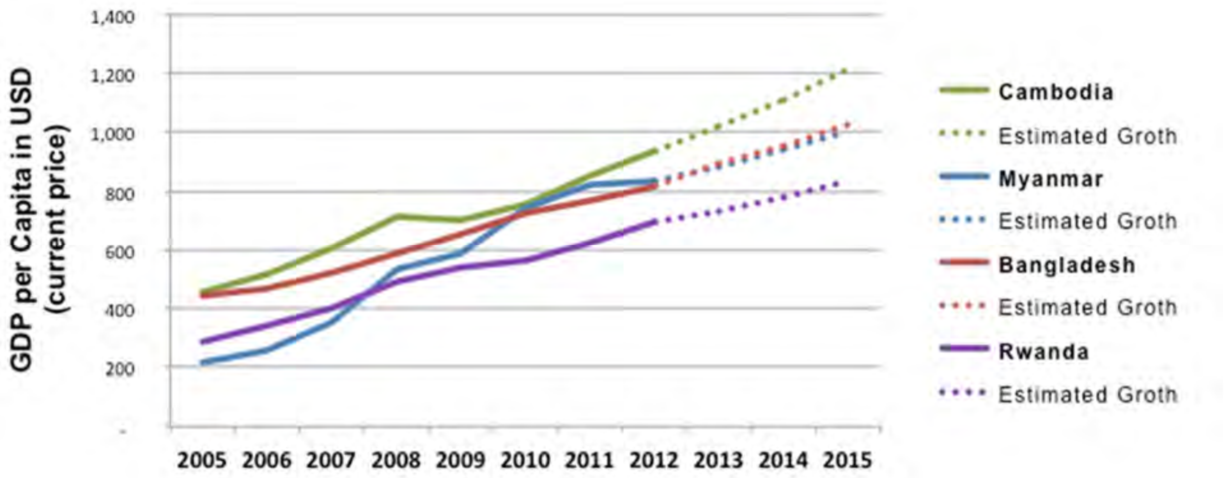

FIGURE 1 GROSS DOMESTIC PRODUCT PER CAPITA FOR BANGLADESH, CAMBODIA, MAYANMAR (BURMA) AND RAWANDA (CONVERTED TO USD AND IN CURRENT PRICE). THE DOTTED LINE IS THE ESTIMATED GROTH IN THE COMING YEARS. SOURCE: (IMF, 2013)

From this graph it is also clear that Bangladesh is predicted to keep growing with the same rate that it has been doing for the last 5 years. To keep up this development the Government of Bangladesh has a lot of hard decisions to make in the near future. One of the biggest challenges is how to provide the energy needed to sustain an economic growth – both now and in the future. The Government of Bangladesh has stated as a mission for its energy policy to make electricity available to all citizens on demand by the year 2020. This should be compared to only 47 % of the people having access to electricity today (Bangladesh Power Development Board, 2009).

To reach this goal Bangladesh needs to install a lot of new generation capacity. Here lies an opportunity to build in more renewable energy in the system from the start, instead of needing to replace a system dependent on fossil fuel later. To use the country's resources to construct an energy infrastructure based on fossil fuels is therefore not only bad from an environmental perspective – in the long run it is also bad from an economical perspective. The Ministry of Power, Energy and Mineral Resources has recognized this trend in its Renewable Energy Policy, where a shift in the way energy is produced in the world today is discussed:

> *"Worldwide, there is a major transition underway in the energy sector. It is happening due to the following three major reasons:*

i. A decline in fossil fuel availability, their predicted gradual extinction in the next few decades and the resultant price volatility due to demand-supply gap.

ii. The need to drastically cut global emissions for mitigating climate change (80% reduction by 2050).

iii. The need for energy security."

(Ministry of Power, Energy and Mineral Resource, 2008)

1.3 ENERGY IN BANGLADESH

Today still, Bangladesh gets most of its electrical energy from fossil fuels: natural gas (88.4 %), coal (4 %), furnace oil (4 %) and diesel (2 %). The remaining 1.6 % comes from hydropower. This big dependence on non-renewables are likely to remain in the near future but from December 1998 until January 2005 the price for natural gas had already increased by over 35 % (Bangladesh Power Development Board, 2009). Some estimates even predict that all natural gas reserves in Bangladesh are likely to be depleted already before 2020 (UNEP & GEF, 2007). Also, on a global level the demand for natural gas has increased a lot and in 2010 natural gas consumption was the fastest growing fossil fuel in the world (International Energy Agency, 2010). This increased competition for the gas drives the cost up on the international market, and together with an expected increase in import of natural gas in the future, this will be a significant cost-increase for the people in Bangladesh.

This increased dependence on gas is of course tragic, as it will have many negative consequences for the country in the future. But when looking at the total use of energy and not only on the electricity production and transportation, the future is not quite as dark. One other big source of energy is biomass for household-cooking and small industries in rural areas. Unfortunately the way this resource has been used cannot be called sustainable as it has led to deforestation, and the dependency of this energy source will therefore need to decrease in the future. This mainly hurts the 100 million people living in rural areas where the living standard already is very, very basic. For instance, about 40% of the population in Bangladesh lives under the line of poverty, which is defined as having an income of 1 USD per day (Carlsson & Widlund, 2008). On top of this Bangladesh is often hit by natural disasters. On average about 25% of the whole country get covered by a flood annually, and every 4-5 years about 60 % of the country is covered. This has led to big economic losses every year, and this is only expected to increase along with the global temperature of the world. (The World Bank, 2010) To tackle these floods, Bangladesh is creating draining-systems and creating plans for how to react to these floods. But in a country where every available square meter is used for living, farming or to grow trees, these floods still create big damages. United Nations Development Programme (UNDP) made a country evaluation in 2005, where they estimate that between 0.5% and 1% of Bangladesh's annual GDP during the last 10 years had been lost in direct costs of natural disasters (UNDP, 2005). These floods will hit the poorest the hardest and an increased number of big floods are therefore directly contradicting the Poverty Reduction Strategy from the Government of Bangladesh. Thus it is not strange that the strategy very clearly states concern due to the big dependence on fossil fuels:

> *"The prospect of depletion of non-renewable energy sources stands out as one of the major concerns of mankind today."*

(General Economics Division, Planning Commission, GOB, 2005)

One important solution to many of these problems is more renewable and local energy production. It is not a magic bullet that will fix everything but it is an important step in the right direction (for more discussion around the benefits of developing the local renewable market see section 2.1 Developing the local market).

1.4 RENEWABLE ENERGY SOURCES IN BANGLADESH

Looking at the possible sources of renewable energy in the world today, solar, wind and hydropower together with biomass are some of the most developed technologies. Some of these are more common and easier to use in Bangladesh than the others, so below are the current use and possible use in the future stated for some of these energy sources.

1.4.1 BIOMASS

Biomass is one of the oldest types of energy used by humans, and counting all types of biomass used in Bangladesh it forms over half of the total energy supply (mostly cooking in rural areas, and rural industries). But most of it comes from cow-dung, rice hulls and other waste products from farming as well as from farm animals. (UNEP & GEF, 2007) Considering Bangladesh's high population density there is not really any space to increase the production of biomass anymore. So the big hope is to use the available energy more efficiently with better technologies – such as more efficient stoves for cooking. The Bengali Ministry of Power, Energy & Mineral Resources also recognizes this and states on their homepage that:

> *"Moving towards energy sustainability will require changes not only in the way energy is supplied, but in the way it is used, and reducing the amount of energy required to deliver various goods or services is essential."*

(Ministry of Power, Energy and Mineral Resource, 2010)

One program focusing on this issue is the Sustainable Energy for Development (SED) – a cooperation between the German Federal Ministry for Economic Cooperation and Development and the Bangladesh Ministry of Power, Energy, and Mineral Resources. The SED-program has together with a group of scientists at the Institute of Fuel Research and Development (IFRD) of the Bangladesh Council of Scientific and Industrial Research, developed a more efficient stove that can be produced for around 800 TK (about 66 SEK[a]). These new stoves can reduce the biomass needed to cook a meal by 50%. (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2012) With a more efficient use of the biomass available, new investments in fossil fuels can be reduced and the resources available can be beneficial for even more people.

1.4.2 BIOGAS

But to only us the current technology more efficiently is not enough. Therefore has a lot of interest been put into develop another related fuel called biogas. Biogas has a good potentiality to be an important player in the Bengali energy market in the future. Due to the big amount of farm animals, both NGO's and the Government are hoping that biogas produced from waste products from animals and households can grow a lot. Bangladesh already uses a lot of natural gas on all levels in the society. Therefore both the infrastructure and the know-how for dealing with gas exist throughout the population. According to the Renewable Energy Policy of Bangladesh from Nov 2008, there were tens of thousands of households and villages all over the country that had some kind of biogas plant (Ministry of Power, Energy and Mineral Resource, 2008). Other sources give this number to be about 40,000 households and villages, and this figure is only expected to grow in the future, thus having an important place in the renewable mix in Bangladesh. But even with the help of biogas, bio-energy cannot cover all the future energy needs of Bangladesh on its own.

[a] Calculated with an exchange rate of 1 Tk (also called BDT) = 0.083 SEK (on January 3, 2012).

1.4.3 HYDROPOWER

Hydropower has a place in Bangladesh, but only to a limited extent. To start with Bangladesh is a very flat country where two-thirds of the area is less than 5 meters above the sea level (The World Bank, 2010). This limits the amount of good locations available for hydropower and the few locations available have already been exploited. Because hydropower is relatively cheap and much more reliable than other renewable energy sources it is usually one of the first ones to be developed and in 2009 hydropower already contributed 4.2% of the total installed production capacity of electricity in the country. Looking at the energy generated in kWh per year on the other hand, hydropower only contributed 1.6 % of the electricity produced in 2009. (BPDB, 2009)

As long as Bangladesh cannot develop technologies to utilize the energy in the annual floods, or extract energy from the flowing rivers without needing a dam, hydropower will remain to have a very limited impact on the energy production in Bangladesh also in the future.

1.4.4 WINDPOWER

For wind power, the good wind resources are limited to the coastal areas according to the Renewable energy Policy of Bangladesh mentioned above (Ministry of Power, Energy and Mineral Resource, 2008). A study by Khan et al. also finds that the annual average wind speed in this region is above 5 m/s at a height of 30 m (Khan, et al., 2003). As can be seen in Figure 2, most of the non-coastal areas are having a too low wind resource even to be marked on the map, showing that big parts of Bangladesh are not suited for big investments in wind power with current technology. A usable wind resource is normally from 3 m/s and above 25 m/s the wind turbine is shut down for safety reasons. The best value is therefore between these two values where an annual wind speed of 5 m/s is good but not superb. Because the power generated increase with the cube of the wind speed, a higher annual wind speed becomes very beneficial.

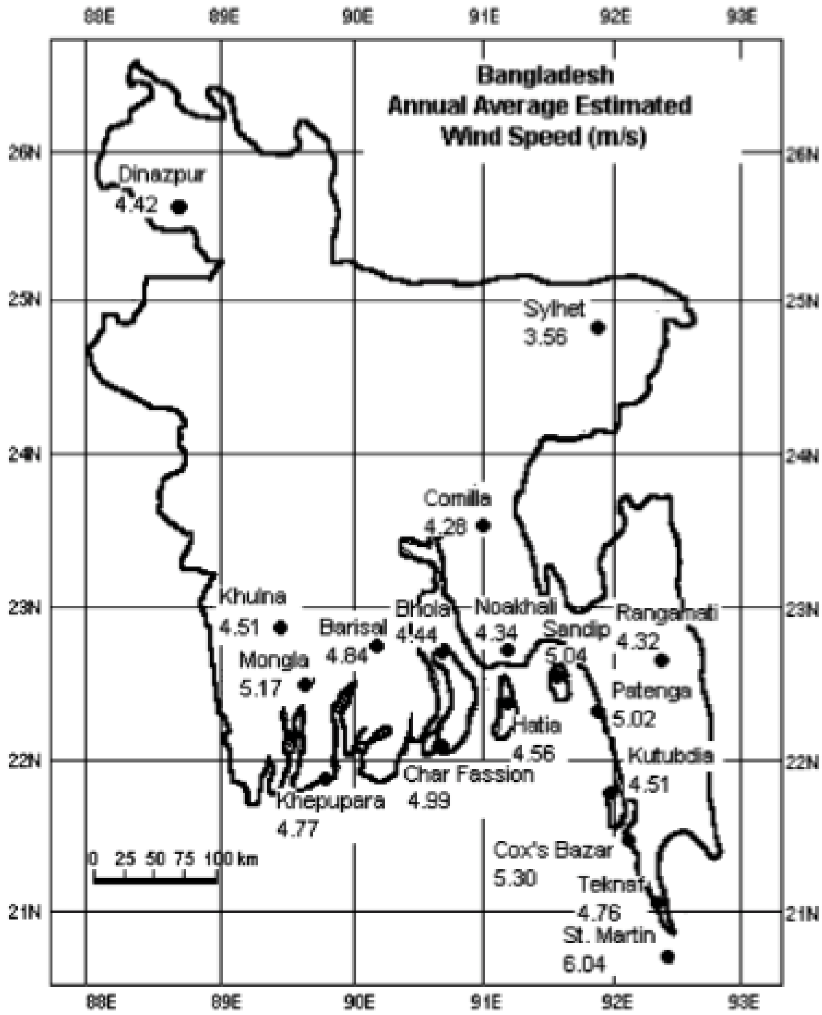

FIGURE 2 MAP OF BANGLADESH WITH WIND SPEED IN M/S MARKED FOR SOME LOCATIONS. SOURCE: (KHAN, ET AL., 2003)

In a study of the Solar and Wind Energy Resource Assessment[b] (SWERA) in Bangladesh the annual wind speed is only 3.3 m/s, at a height of 10 m in Bogra where this study was conducted (SWERA, 1987-2000). This is usable but not with a big margin. On the other hand there is another renewable energy source that could be much more interesting to use more in Bangladesh – the sun!

[b] For more information about SWERA see APPENDIX B: Data from SWERA.

1.5 SOLAR ENERGY IN BANGLADESH

1.5.1 SOLAR THERMAL BETTER AT PRODUCING HEAT

To use the sun as a heat source is not a new idea of the twenty-first century even if we seem to think so at times. Already Leonardo da Vinci proposed to use solar heat for industrial usage in the sixteenth century, but the technology was not ready at that time (Butti & Perlin, 1981). Lately, both the technology for producing electricity and the technology for producing heat from solar energy have advanced a lot.

PV systems can produce electricity locally and will, alongside the other renewables mentioned in the section above, be an important part in giving the whole population of Bangladesh access to electricity by 2020. The biggest challenge to this reform is that currently, the electricity produced in Bangladesh is sold under the production cost. While the average tariff is Tk. 2.56 per kWh, the average cost of supplying the same kWh is Tk. 3.07 (Bangladesh Power Development Board, 2009). As long as the same support is not given to PV systems – they will have a hard time competing in areas that have access to the electric grid. But as mentioned above still less than half of the population in Bangladesh has access to the electric grid, and in the rural areas as few as 30% of the households has access to the electric grid. This fact, together with the hard work of many solar-advocates and the Rural Electrification and Renewable Energy Development (RERED) project has managed to boost small-scale Solar Home Systems in rural areas. According to one of the blogs of the World Bank, End Poverty in South Asia:

> *"More than 750,000 remote households and rural shops have already been connected to Solar Home Systems."*

(Ahmad, 2011)

But for the application of producing heat, the use of a PV system would be a big waste of energy; a much better alternative for this application is to use a solar thermal system. And because a solar thermal system can be made very simple, it can also be much cheaper to produce. Therefore, the focus of this investigation has been on the use of a solar thermal system.

1.5.2 SOLAR IRRADIATION AVAILABLE IN BANGLADESH

Having good technology is important but another important part in choosing the right system is the available solar resource. To choose the right type of solar thermal system there are two important parameters to take into consideration:

1. The total energy available per square meter and day, usually given in MJ/m^2 and day [c] (or kWh/m^2 and day)
2. The ratio between direct and diffuse solar radiation

Where the direct sunlight is the light from the sun that hits the collector directly and the other parameter, diffused light, comes from the sunlight that is been absorbed by clouds and other particles on its way through the atmosphere. The absorbed light is then emitted in all directions, thus creating a less intense and more spread out light that hits the collector (and everything

[c] When writing "MJ/m^2 and day" in this paper, it means $MJ/(m^2 \bullet day)$

else) from all directions. Some of this light is therefore hitting the collector even when no direct sunlight reaches the collector.

Different technologies are better at utilizing different types of solar radiation, where concentrating collectors are very dependent on the direct component of the sunlight. A non-concentrating collector will not reach as high temperature as a concentrating collector, but on the other hand the diffuse component will contribute more to the total energy input. To evaluate the solar resource at any specific place, it is important to assess the solar irradiation in the area over longer periods, such as a month, a year and preferably even several years – to gain a better understanding of the long-term possibilities. In this study, data from SWERA has been used for annual values and then compared with measurements made during the days when experiments were conducted.

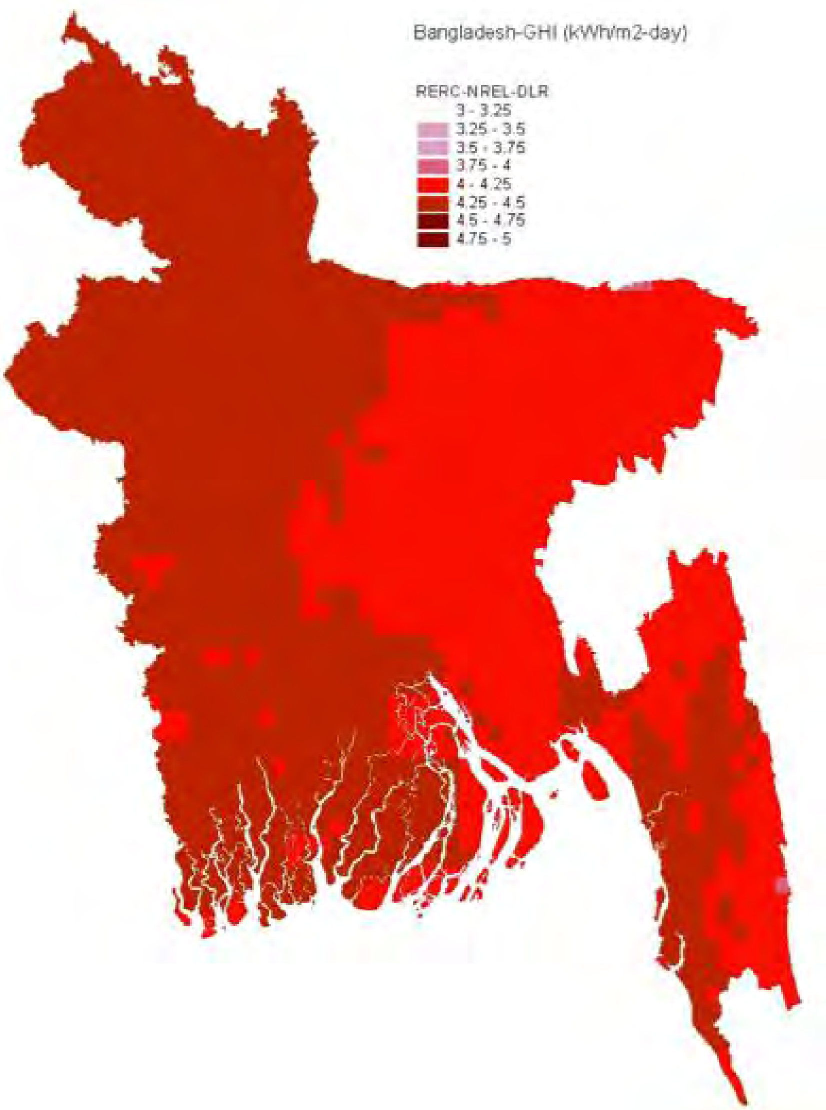

FIGURE 3 GLOBAL HORIZONTAL IRRADIATION (GHI) MAP OF BANGLADESH SHOWING AVERAGED DATASETS TUNED TO DHAKA, WHERE 3 KWH = 10.8 MJ AND 5 KWH = 18 MJ. SOURCE: (UNEP & GEF, 2007)

The month with the lowest irradiation is December (13.7 MJ/m^2) and April is the month with the highest irradiation (22.2 MJ/m^2), which means that the collector mentioned above, in Bogra would produce 42.5 MJ more on a day in April compared to a day in December. The daily total irradiation for this region can be seen in Figure 4 together with the average irradiation per month as well as the annual average. From this figure it's clear that the average value for February (16.8 MJ/m^2) and the annual average value (17.2 MJ/m^2) are almost the same, thus making February a good representation for the rest of the year.

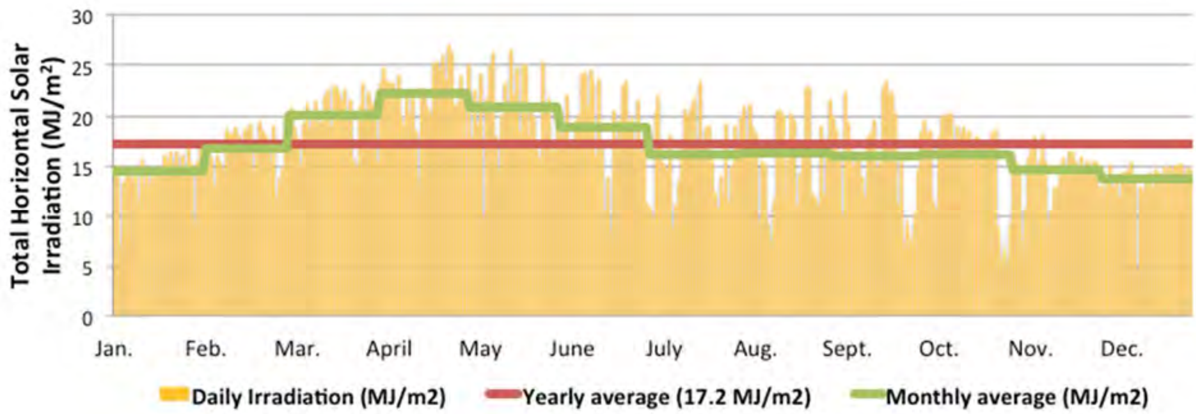

FIGURE 4: TOTAL SOLAR RADIATION FOR BOGRA (MJ/M^2). SOURCE: (SWERA, 1987-2000)

Because Bangladesh is located on the northern hemisphere the months of June to August have the longest days. It is also the time when the sun reaches highest on the sky, meaning that the sunlight travels the shortest path through the atmosphere at midday on a summer day. Because the atmosphere absorbs and scatters more of the light the longer the path is, the natural assumption is that the irradiation should be highest in July and not in April. But to understand this better it is important to remember that the light can be seen as a sum of two components – one Direct Normal component and one Diffuse Horizontal component (as is shown in Figure 5). It is then clear that the diffuse component is dominating from May to September (and on pair with the direct components in October) meaning that a lot of the direct light does not reach the ground contrary to the expected scenario. The main reason for this can be understood by studying the average rainfall in Bangladesh over a year.

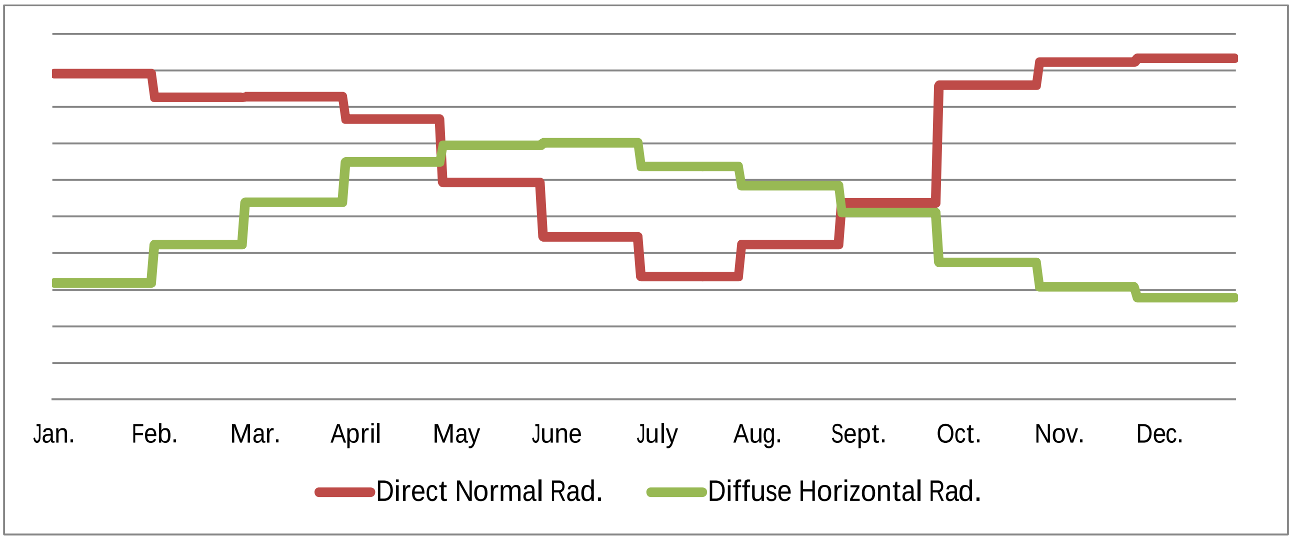

FIGURE 5 MONTHLY AVERAGE VALUES FOR THE DIRECT COMPONENT AND THE DIFFUSE COMPONENT OF THE LIGHT HITTING THE COLLECTOR. ABOUT 40 % OF THE RADIATION CONSISTS OF DIFFUSES LIGHT.
SOURCE: (SWERA, 1987-2000)

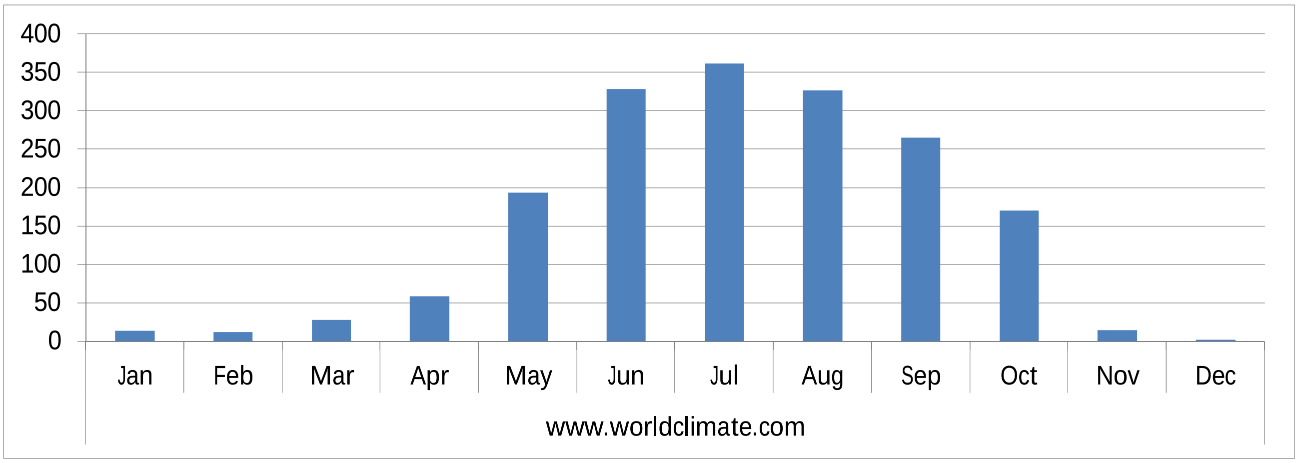

FIGURE 6 AVERAGE RAINFALL IN BOGRA, BANGLADESH (MM PER MONTH).
SOURCE: (THE GLOBAL HISTORICAL CLIMATOLOGY NETWORK, 1992)

During the rainy season a lot of clouds are formed and these clouds prevent a lot of the direct sunlight from hitting the ground. As shown in Figure 6 most of the rain falls in May to October and as seen in Figure 5 this correlates very well with the months when the diffused light is the dominant source of solar energy. This means that in total over a whole year the diffuse light in Bangladesh contributes to as much as 40 % of the total solar irradiation, thus making a technology using concentrating solar energy much less attractive.

The total energy available in Bangladesh is still very high even if a big portion of the theoretically possible irradiation is lost in the clouds during the summer. To understand how good the solar resource in Bangladesh is, a comparison can be made with Germany that is one of the world’s leading countries in solar power today.

1.5.3 SOLAR IRRADIATION AVAILABLE IN GERMANY

In Germany the annual solar irradiation varies from about 9 MJ/m^2 and day in the north to 12.6 MJ/m^2 and day in the south (Meteonorm, 2008). This means that the irradiation in December in Bangladesh still is higher than the annual average in southern Germany. Also the variation over the year is much less in Bangladesh, creating a more even energy production over the year. In Stuttgart, a city in the southern parts of Germany the average solar irradiation is about 11.2 MJ/m^2 and day. The lowest value for Stuttgart (also in December) is only 2.7 MJ/m^2 and day while the highest irradiation is in July with 19.6 MJ/m^2 and day. (Duffie & Beckman, 2006) For a 5 m^2 collector this gives a difference of 84.2 MJ/day between highest and lowest irradiation – which is twice as big as the difference in Bangladesh. With this great solar resource Bangladesh would gain a lot from using more solar energy in the future.

2 HANDMADE PAPER – A TOOL TO CREATE A BETTER FUTURE

Many parts of a renewable energy system can be produced locally. Also the energy generated can be used locally to cook food, heat water for households, or used in small-scale industries. This can both help develop the society and create well needed jobs in Bangladesh.

One example of this is Prokritee, a NGO created by Mennonite Central Committee (MCC) in Bangladesh with the goal to create jobs for poor women and men. Prokritee produce handmade papers and are (when possible) already using the direct sunlight to dry papers but want to take that initiative one step further by participating in this study. The goal of the study is to use a solar collector to produce heat that can dry papers in an environment similar to the current drying rooms, and by doing so eliminate or reduce the use of wood and natural gas for this task.

2.1 DEVELOPING THE LOCAL MARKET

Even if many good reasons to strive towards more renewable energy sources already have been put down, one more important reason remains to be mentioned. By focusing the development on use of local technology, the local business is being developed and in the long run this will help develop the country as a whole. To merge this goal with renewable energy production is very sensible because renewables are generally produced on a smaller scale, and distributed over a big area. This is also reflected in the Poverty Reduction Strategy from the Government of Bangladesh that state that:

> *"Though energy derived from oil, gas and coal will play a vital role in meeting a growing demand for many years to come, the realisation of the possible exhaustion of the world's fossil fuels has focused interest and effort on harnessing alternative energy resources."*

(General Economics Division, Planning Commission, GOB, 2005)

Another actor that thinks this way is the Ministry of Power, Energy and Mineral Resources that wrote the Renewable Energy Policy of Bangladesh. The Ministry believes in this so much that it put up as one of its goals to:

> "*Promote development of local technology in the field of renewable energy*."

(Ministry of Power, Energy and Mineral Resources, 2008)

By increasing the technical knowledge in this field, many people can be helped away from poverty and at the same time help the local economy to grow. And by growing the market on both the supply and the demand side, a positive feedback loop can be created where the people earning money on the renewable energy can use this money to invest in more production that generates more income and create new jobs.

2.2 JOB CREATION IN BANGLADESH

One project to develop the local market in Bangladesh was conducted already in 1986-87 by the Mennonite Central Committee (MCC). MCC had employed Mr. Abdur Rab, Mr. Iqbal Hussain and other skilled people to investigate the possibility of starting to produce hand-made paper in Bangladesh. The hope was that handmade papers as well as products made from the papers could be exported to other countries, thereby creating jobs in Bangladesh. By 1988 the papers produced had the quality required and a first production center could be built in Feni under the supervision of Mr. Rab. This turned out to be a successful idea, and today Mr. Rab has built his own factory for producing handmade paper while MCC have gone on to build a total of four centers including the one in Feni. The latest was built in 1993-94 and today even the smallest of these centers employ 60 people while the biggest employ over 100 people. Out of which two thirds are women and most of them have lived very challenging lives due to poverty and/or social injustice before being employed by MCC. (Das, 2010)

MCC has also been successful in developing a growing export market in the West for products made from handmade paper in Bangladesh.

FIGURE 7 MCC BANGLADESH'S DESCRIPTION OF THEMSELVES ON THEIR WEBPAGE. SOURCE: (MCC BANGLADESH, 2011)

2.2.1 SHORT BACKGROUND TO MCC

The Mennonite Central Committee is a North American aid organization that has been active in Bangladesh since 1970, which was even before the Bengali independence in 1971. MCC entered Bangladesh after a devastating cyclone hit the region in 1970 and after the war for independence MCC helped rebuild the country again (MCC Bangladesh, 2011). Today MCC works with several partner organizations in Bangladesh to create jobs develop agriculture and build peace between different ethnic and religious groups along many other things.

2.3 PROKRITEE

In 2001 MCC spun off most of its handicraft businesses from the Job Creation program within MCC into an independent local not-for-profit company called Prokritee. Prokritee today has the main responsibility for marketing, management, design and finance – all areas that were provided by MCC before. Prokritee is today headed by Swapan Kumar Das, a former employee at MCC and with good insight in the whole process. Prokritee still has some cooperation with MCC but is an increasingly independent organization totally controlled and operated by local employees. (Das, 2010)

MCC's staff is today working a lot through partner organizations instead of doing all the work themselves. Their main contribution is instead to supply valuable knowledge and expertise not available in the partner organizations. One such example is a center for development of sustainable technology for rural areas located in Bogra, Bangladesh. At this center local and foreign engineers work on solving different problems facing the population in rural Bangladesh. The projects vary from the best way to produce ecological fertilizers with the help of composting, to developing modern building techniques using locally available resources. Another ongoing project evaluates the usefulness of solar panels for light and domestic appliances in the housing connected to the center, as well as trying new techniques for farming. To be able to work with this variety of projects, a lot of good equipment is available at the center – but many times the employees still had to find a simple solution to solve quite difficult problems.

2.4 DRYING HANDMADE PAPER IN BANGLADESH

2.4.1 DRYING THE PAPER – AN ENERGY INTENSIVE PROCESS

As mentioned earlier has the paper production centers in Bangladesh been a successful project this far, but the situation in Bangladesh has changed a lot since the early 1990s which forces Prokitee to adjust their production to the new playing field. One such change is the increasing fuel cost that makes the energy consumption of the centers an increasingly important parameter when planning for the future. This has led to an interest in re-evaluating the current technology used for drying papers even if they have been very successful up to now.

One of the most energy intensive parts in producing paper is the drying process, because the water that is hardest to evaporate is located in the core of the papers, inside the very fiberes that the paper is made of. Even in the highly efficient processes used in conventional paper production, the drying process consumes about two thirds of the total energy demand. The water content is then usually reduced from 55-65% before drying, to about 5-10% after drying – to dry the paper even more would cost a lot extra energy for no gain. Optimally the water content in the paper should be on the same level as the humidity level in the storage where the paper will end up (for more details see section 5.1 theoretical background: To dry Papers). (Persson, 1996)

2.4.2 SUN DRYING – USING THE FREE ENERGY FROM THE SUN

Handmade paper is often produced in countries with less access to energy sources and more access to cheap labor. The energy intensive drying process has therefore often utilized so called 'sun drying' to dry the papers (as seen in Figure 8). This mean that the papers, are placed on a frame and then placed under direct sunlight (after pressing out as much water as possible) to be dried by the sun.

FIGURE 8 PAPERS DRIED IN THE SUN AT SHUKTARA CENTER IN FENI, BANGLADESH. PHOTO: MIKAEL HJORT

The difference compared with solar drying is that in sun drying the sun's heat is used directly and no solar collector is required, which makes it very simple to use. On the other hand there is also some important drawbacks with sun drying. Firstly, it is highly dependent on the weather because papers can only be dried when the sun is shining, when the wind is calm and when there is no risk of rain. This limits the amount of days of the year when papers can be dried in the sun and can therefore create a bottleneck in the production. Secondly, it takes very long time to dry thicker papers even under optimal conditions when using sun drying, because the temperatures are lower.

When using solar drying the energy can be gathered from a bigger area and concentrated to a smaller drying surface, thus increasing the temperature of the drying process. To compensate for this while using sun drying, a lot of papers are dried at the same time in big open areas. But as a result, it is then harder to supervise the drying rate in all the papers. Therefore the papers are often left in the sun longer time than required to ensure that they are dry when collected. If the paper does not dry fully in one day, it can develop wrinkles and defects overnight thus, reducing the quality of the paper.

2.4.3 SUN DRUING VERSUS CONVENTIONAL DRYING

At the centers many different types of fibers and thinknesses of the papers are produced (such as silk, cotton, jute, water hyacinth and straw). After drying, the papers are made into products like gift cards, note books, lanterns and paper decorations. To optimize the drying process for each of the different papers produced at the centers, both sun-drying and conventional drying with auxillary heat is used today. That way it has been possible to optimize the use of the free energy coming from the sun to dry thinner papers and only spend auxiliary heat to dry the thicker papers.

The silkpapers are always dried in the sun while the other types of papers are divided into 'thin papers' and 'thick papers'. The thick papers are then dried on specially designed drying drums (seen in Figure 9).

FIGURE 9 BLACK PAPERS DRIED ON GAS-HEATED STEEL DRUMS AT SHUKTARA CENTER, BANGLADESH.
PHOTO: MIKAEL HJORT

The drying drums (hereafter also called the driers) are placed under a roof and on three sides surrounded by walls, while the fourth side of the building is completely open for accessibility. The walls keep more of the heat in the air surrounding the driers as well as protect the papers from rainfall. This way the driers can be used also during the rainy season, and thereby enabling the centers to keep production going during the whole year.

2.4.4 CURRENT TECHNOLOGY USED BY PROKRITEE

An employee at MCC's job creation program named I. Hussain constructed the drying process currently used in the centers during the 1980s. The construction was inspired by a visit to a similar facility in Japan and the basic concept is a steel drum heated inside by steam from boiling water. The water is placed in a square shaped metal box without lid called a boiling-tray. The tray is then placed on the bottom of the drying drum, and a fire underneath it heats the water to boiling temperatures inside the drum, thereby producing steam that heats the drum (seen in Figure 10). The condensed water then flows back to the boiling-tray inside the drum and can be heated anew – thus in theory creating a closed loop.

The papers are then stuck on the outside of the drum (see Figure 9) with the help of a very light glue to maximize the contact surface between the paper and the drum throughout the whole drying process. In some of the centers gas pipelines are available and therefore these facilities use natural gas instead of firewood to boil the water. Both of these energy sources are very reliable heat sources and independent of electricity – something that has been very important in Bangladesh up to now.

But there are also some big drawbacks with this design.

FIGURE 10 BOILING TRAY LEAKING STEAM AT BIBORTON CENTER. ENERGY SUPPLIED BY BURNING FIREWOOD.
PHOTO: DANIEL THOMAS, MCC.

2.4.5 DRAWBACKS WITH CURRENT TECHNOLOGY

Firstly, there are big losses in the form of steam leaking out from the drum (as can be seen in Figure 10). Because the water changes from a liquid into vapor the volume increases a lot, so if more water is evaporated than condensed inside the drum, the pressure goes up. This should in theory not have to be a problem if the flame, and thereby the heat added to the water in the boiling tray, could be regulated more exactly. That would then make sure that the air-water vapor mixture was kept at a constant atmospheric pressure. But as the current overblow-protection is just a hole, any overpressure that builds up inside the drum will push out the hot air and steam inside of it. In reality therefore this situation is not working well and a lot of energy that has been used to vaporize the water is lost with the steam that is leaking out.

The second big problem is corrosion. In order to keep the cost down all the current drying drums except one is made from ordinary steel and not from stainless steel. This has led to big corrosion problems inside the driers (as seen in Figure 11) because of the moist environment where new oxygen easily can enter the driers.

FIGURE 11 DRYING DRUM AT SHUKTARA – OUT OF USE DUE TO EXTENSIVE CORROSION.
PHOTO: MIKAEL HJORT

Because of this, the drums have been so damaged that they need to be replaced every 20 months (Das, 2010).

The third problem is that burning wood can be seen as environmentally friendly and sustainable as biomass is regarded a renewable energy source by many, but there are many drawbacks of using firewood under these circumstances. To start with it creates a lot of smoke, and it has not been possible to ventilate away all smoke from the rusty driers – creating a smoky working environment for the workers in the centers. According to the World Health Organization (WHO) every year nearly 2 million people die prematurely due to illnesses attributable to a smoky indoor environment or as they call it: "*air pollution from household solid fuel use*" such as wood, animal dung, crop waste and coal (WHO, 2011). Another important issue is that wood is only "renewable" as long as the forests grow back again. In Bangladesh only 11 % of the land area is covered by forests and it has been decreasing with 0.2 % annually for the last 20 years (FAO, 2011). This increases the cost of wood, as easily accessible forests are cut down and at the same time, the decreasing areas with a forest cover reduce the habitation for wildlife. One evidence for the decreased possibility to rely on firewood as a heat source in the future that can be mentioned is that the Department of Environment in Bangladesh has pressured one of the centers to stop using firewood as fuel for drying and pulp production.

2.4.6 COSTS OF CURRENT TECHNOLOGY

All these inefficiencies lead to higher operational costs at the four production centers, which have:

- 18 driers that are 8 ft. long and can dry 12 papers simultaneously (one such drier is seen in Figure 9 and each drier costs about 15,000 Tk to replace), and
- 4 driers that are 16 ft. long and can dry 24 papers at the same time (each costing about 25,000 Tk to replace) (Thomas, 2010).

Each year there is also a cost to repair the driers before they are so broken that they need to be replaced (about 2,500 Tk per drier and year). This leads to a total cost per year of 280,000[d] Tk (about 24,000 SEK[e]) for repair and replacement of all the driers. In order to reduce this cost a test drier has recently been constructed out of stainless steel and is therefore expected to have a longer lifetime, but at the same time the cost of construction increased to 47,500 Tk for a small drier – almost tripling the initial cost of a drier.

On top of this, firewood in Bangladesh is getting more expensive. In a little more than a year the price has increased with 50 % according to Swapan Kumar Das CEO for Prokritee (Das, 2012). And comparing the cost in 2012 with the cost in 2010 the cost has increased over 100% according to D. Thomas. On average one 8 ft. drier requires 60 kg of wood per day, and the 16 ft. ones about 100 kg per day (Das 2010; Thomas 2010). With a cost of 130 Tk/mon, and one mon equaling 37.5 kg[f], the cost for firewood per kg in 2012 is about 3.47 Tk/kg. This gives an annual fuel cost of 54,000 Tk for a small drier and 90,000 Tk for a big drier (calculating on 5 drying days per week, and no holidays during the year[g]).

At another plant natural gas is used instead and the yearly cost of gas is about 370,000 Tk for the whole center. Assuming that this system uses as much as 80 %[h] of the total energy consumption for drying, and that 6 driers have been in operation simultaneously during the year of 2010 – the fuel cost per drier and year ends up to about 50,000 Tk (other types of use for the gas is to heat the pulp, but this requires much less energy than drying the papers).

As a reference another big cost that can be interesting to compare with is the salaries of the workers. The workers have a decent salary for Bengali standards, with an average salary just above 40,000 Tk (or about 3,300 SEK) per year and worker. Due to the different sizes of the workforce this adds up to a fixed cost 2,400,000 to 4,000,000 Tk per center and year. Even if this cost is much bigger than the total costs of the fuel together with the cost of replacing the driers every second year, the later adds up to a substantial amount of the total cost per year for Prokritee (about 1,350,000 Tk/year). And on top of that another 340,000 Tk/year is used for pulp production[i].

[d] 280,000 = 25,000 * 12/20 * 4 + 15,000 * 12/20 * 18 + 2,500 * 22

[e] Calculated with an exchange rate of 1 Tk (also called BDT) = 0.083 SEK (on January 3, 2012).

[f] In Bangladesh many people would round up 1 mon to 40 kg, which results in a cost of 3.00 Tk/kg, but this is not confirmed in this case and therefore the official value of 37.5 kg/mon has been used here.

[g] Normally the centers operate 6 days a week except on holidays. To compensate for the holidays a working week of 5 days has instead been assumed here.

[h] The value of 80% for drying comes from one of the centers called Bonoful. They estimated that for every 1 mon of firewood used for pulp production, a use of 4 mon was required for drying the papers produced.

[i] Here assuming that the energy consumption at the centers is divided as: 80% for drying and 20% for pulp production.

2.5 SOLVING THE PROBLEM WITH SOLAR HEAT

The increased fuel costs mentioned above lead to the conclusion that even if Prokritee would change all the driers to stainless steel driers but use the same general technology they would only save 14% of the 1,690,000 Tk mentioned above, as 86% of the total cost comes from the cost of fuel. To make a big impact the drying process needs to be redesigned from the ground and fundamentally different technologies evaluated. As the goal was to minimize the cost of fuel and the resources available in Bangladesh are running ever more scarce, a natural choice was to evaluate the use of solar energy to heat the driers. To do this, a project was created between Prokritee, MCC's Sustainable Technology Center and M. Hjort at Uppsala University in Sweden. D. Thomas, an engineer educated in the USA and currently working for MCC in Bangladesh, in many ways was the driving force behind the creation of this project.

The main objective was to evaluate the possible use of Solar Thermal energy to reduce the fuel consumption in drying the handmade papers at Prokritee's centers in Bangladesh. By moving from environmentally damaging fuels to solar thermal, Prokritee hopes to improve both the long-term economy of the program as well as shift to a more efficient drying system with fewer losses. If successful, this could also encourage other paper-producing facilities to switch to a more sustainable energy source. This would be beneficial for Bangladesh from both a local and a global perspective, considering the big consequences the global warming is predicted to have in the region.

2.5.1 DIVISION OF CONTRIBUTIONS AND RESPONSIBILITIES

Because the economical benefits of the project would go to Prokritee, they also agreed to fund the project by buying a collector and the material to build a new type of drier that could be heated by the collector. Design of the system was to be agreed upon between M. Hjort and D. Thomas, and the testing of the system would then be conducted at MCC's Sustainable Technology Center in Bogra by M. Hjort. All construction work would be contributed by staff from MCC or purchased by local craftsmen, and as much as possible of the material used was to be obtained on the local market. It was hoped that this would make repairs and replacements possible without the help of import from the USA or Europe. MCC also agreed to contribute with housing at the center for M. Hjort during his stay in Bangladesh.

2.5.2 MAIN OBJECTIVES WITH THE PROJECT

Because no work has been made in this area before, a small-scale preliminary study to be conducted in Bangladesh was considered necessary as a first step in the extended project of replacing the current driers. In concrete terms the first phase of the project aimed to give clear answers to three overall questions:

4. What is the useful heat output from an evacuated tube solar collector operated under typical conditions in Bangladesh?
5. How big part of the heat produced can be converted into useful heat to dry papers?

6. Which of the following parameters are most important to estimate the energy needed to dry a paper?
    a. Water content in the paper
    b. The fiber used in the paper
    c. Temperature of the drier

3 DESIGNING A NEW SYSTEM FOR DRYING

Three different types of systems using different media as the heat carrier were evaluated against each other: System A used hot air to transport the heat, System B used an air-vapor mixture and System C used hot water. In spite of a similar way of operation the third option was redesigned in a way that is thought to increase the efficiency of the system and was therefore chosen.

Next step was to choose a solar collector, the pump, filter and all measuring equipment needed to complete the setup, where a lot of effort was put on calculating the aperture area needed for the solar collector.

3.1 DESIGNING A NEW DRIER SYSTEM

To answer the research questions, a new drying system first had to be designed. Initially three different setups were discussed but all three would use a solar collector to generate heat.

A. In the first setup the collector would heat air that then would be blown over the papers, thus heating the papers and at the same time removing the moisture in the surrounding air.
B. The second setup was basically a copy of the old system but instead of a boiling tray a solar collector would heat the water into steam and then lead it into the drier where it would condense again.
C. The third and last option was to heat the water to a high temperature but not beyond the boiling point. By only dealing with liquid water, a pump could be used to regulate how fast the hot water would be circulated in the system.

Some of the benefits and drawbacks are the same for the three systems so a table listing all the relevant features can be seen in Table 1 under section 3.1.4 Summary of all Systems.

3.1.1 SYSTEM A

System A had some interesting benefits but also a lot of uncertainties coupled with it. As this system would have been so different from the other systems it was hard to evaluate exactly how much better/worse it would be at performing some tasks. One of the interesting benefits was that just as clothes dry in the wind even on a cloudy day, the papers would dry in the wind even if the temperature would not be super-hot. Just by removing the moisture around the papers and then replace it with dry air this drier could probably be used both day and night. But on the other hand, if the surrounding air would be very moist this system might not work very well even when the sun is shining. To deal with this auxiliary energy might be needed to heat the air or at least to remove the moisture from the air.

One drawback in choosing this system would be that it would be hard to predict how big the collector need to be because of the difficulties in predicting the efficiency of the system and how much energy that would be lost with the exhaust of warm moist air.

To minimize this loss the idea was to let the hot air pass many papers (as seen in Figure 12) before being exhausted from the system. The air reaching the first paper would then be warmest and driest, while the air reaching the last paper would be colder and moister. Therefore a transport system would be used, where a dried paper could be taken off in the hot region (called the front of the system), and then all the papers would be moved “forward” one step to allow a new paper to be added in the back of the row.

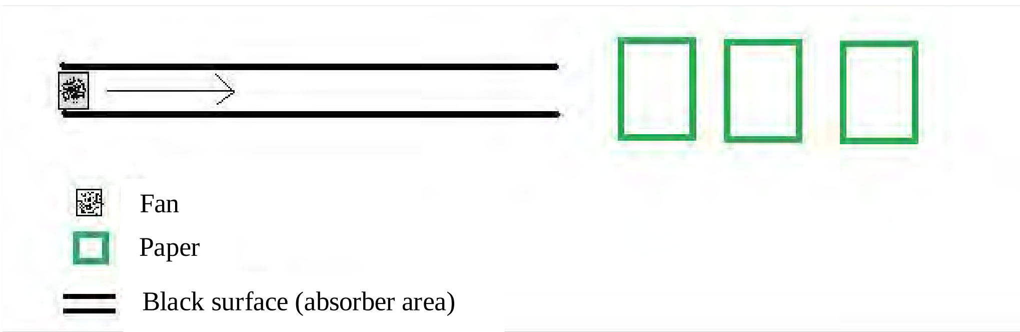

FIGURE 12 SCHEMATIC DRAWING OF AIR BASED PAPER DRIER SEEN FROM THE SIDE.

This system would also be dependent on electricity for a fan to operate. But this need was regarded as a small drawback considering the increased access to the electric grid and the common use of uninterruptible power supplies (UPS). This gives a freedom to use electricity in a way that was not available when the old drier technology was developed.

Finally in the paper industry systems using hot air exists, but are only used for some special papers that cannot be dried with conventional methods (Persson, 1996). More common is to press the paper against heated rolls in several stages, a way that is more similar to the way System B and System C operate.

3.1.2 SYSTEM B

The biggest benefit with System B is the independence of electricity and that the system would be intuitive for the workers to use. System B is basically a copy of the old system, and the only difference for the workers would be that the driers would be heated with solar energy and therefore less smoky. But as mentioned in section 2.4.5 Drawbacks with current technology, the old system has a lot of drawbacks as well – such as the loss of energy in the form of steam that leaks from the drying drum.

This is one of the biggest drawbacks with System B but in theory steam “generates” as much energy when it condenses, as was required to evaporate the water in the first place. The problem is that it requires a lot of energy to produce the steam, so when the steam leaks all that energy is also lost. To understand the magnitude of this loss the energy required to generate the steam has to be calculated:

- To heat water from 10° to 100°C, one need 378 kJ/kg water and then
- To turn the hot water (100°C) into steam requires additional 2260 kJ/kg water[j].

[j] The energy required to turn water into steam is 2260 kJ/kg, while the energy needed to heat

Thus the total energy loss for every kg of steam that is leaking out of the driers is 2638 kJ/kg water. If an auxiliary heat source could be used to regulate the steam production, the energy loss could be reduced significantly but would make the system more complicated, as steam would be produced in at least two different places. On the other hand an auxiliary energy source might be needed anyway to enable drying during cloudy and particularly wet days (such as during the summer rains).

Finally, as it takes some time to heat up the water in the solar collector to boiling temperature the operation time for this system would be primarily during the afternoon when the collector is hot enough to generate steam. Before and after this time the water will be hot (50°-99°C) but not hot enough to turn into steam and therefore not usable in this system setup. It would also be harder to integrate a backup heating system into this setup compared to the setup in System C as it would need to be two parallel systems capable of generating the required steam.

3.1.3 SYSTEM C

Similarly to System A, System C would require redesigning the energy transport in the driers a lot, but when considering the low efficiency in the old system, this was not viewed as a drawback. Also, similarly to System B, System C has the benefit that it can be made to look very similar to the old system, even if the technical function of System C is very different.

As the heat-carrying medium in System C would be water instead of an air-vapor mixture, the energy content per kg would be reduced, but as water has a higher density than the gas mixture the driers would still be more compact and the water would be easier to regulate, as water does not take up much more space when it heats up as long as it stays as a liquid. Therefore, in the system one would not need to worry about pressure building up inside as long as the water stays below 100°C. Also losses from the system would be easy to locate which would make repair easier as it would be clear when something is broken.

On the backside also System C would be dependent on electricity to pump the water around in the system, but as mentioned earlier in section 3.1.1 System A this was not regarded a big problem. A bigger problem would be a need for auxiliary power to heat up the system in the morning or to run the whole system on cloudy and rainy days. The benefit with System C compared to System B in this respect would be that the water could be pre-heated by the solar collector and then heated by an auxiliary source to reach the desired temperature. Also the water can be circulated at any temperature up to 100°C making it possible to dry papers also while the drier is heating up and cooling down (even if drying of course will take longer time when the drier is colder). Without an auxiliary system the primary operation hours would therefore be afternoons and evenings.

3.1.4 SUMMARY OF ALL SYSTEMS

After summarizing the pros and cons of the different systems (seen in Table 1) a decision was made to continue with System C only as it seemed to be the best solution for the application of drying papers.

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the same amount of water from 10° to 100°C is only 378 kJ/kg. **Invalid source specified.**

TABLE 1 COMPARISON OF BENEFITS AND DRAWBACKS WITH THE DIFFERENT SYSTEMS INVESTIGATED.

	System A	System B	System C	Old System
Heat carrier	Air	Steam-Air mixture	Water	Steam-Air mixture
Expected heat-losses?	Medium/High	Medium/High	Medium/Low	High
Dependent on electricity?	Yes, electricity for fan	No	Yes, electricity for pump	No
Need auxiliary power?	Maybe	Yes – to create steam on cloudy days	Yes – to heat up in morning and on cloudy days	Yes, no Solar power available
Time of operation	All day	Afternoon	Afternoon/Evening	All day

3.2 DESIGNING THE DRIER PLATE IN THE NEW SYSTEM

As the drying surface was one of the most important parameters in choosing the new system, the first step in designing this system was to agree on how the new drier (hereafter called the Drier Plate, or DP for short) should look like. As mentioned above, the new drier would be more compact as it will contain liquid water, but it will also demand a tight seal around the DP to keep it watertight. Finally it had to have good thermal properties, as the sole purpose of the Drier Plate is to remove as much energy as possible from the water inside, to the paper stuck on the outside. Finally the DP was shaped into a box for easier construction, as this drier only will be used for experimentation.

3.2.1 REDUCING THE VARIATION IN SURFACE TEMPERATURE

At a visit to Shuktara center in Feni on the 4th of December 2010 the temperature difference on a small (8 ft.) drier was measured. The top of all papers being dried on a drier had approximately the same temperature (about 50°-55°C) while the bottom of the same papers was about 8°C lower than the top. The exception was the paper closest to the boiling-tray where the temperature in the top and the bottom was more evenly distributed.

Reliability of the IR-thermometer

The IR-thermometer used to obtain the temperatures at the Shuktara center in Feni, consistently showed a temperature 15°-20°C lower than the temperature of the water entering the DP at the same time (measured during the initial set up phase of the drying measurements). Later, other more reliable thermistors and thermocouples have been used, but no better temperature measurement exist for the old driers used by Prokritee today. But it is clear that the temperature of the drying drums in the old driers has to be below 100°C. Otherwise no steam would condense on the inside of the drier wall. As an example: the top of a paper being dried on the DP with an inlet water temperature of 70°C was measured to be between 51°-58°C with the IR-thermometer.

Also a bare drier without papers had a fairly consistent temperature in the top (up to 70°C for a bare drier[k]), while the bottom

[k] Note that the temperatures at Shuktara center were measured with an IR-thermometer, so the reflective properties of the material can have impacted on the exact temperature. Thus it is hard to compare values taken from a drying

of the driers cooled down somewhat as measurements were made further away from the boiling-tray.

As the paper quality increases with a more even temperature on the Drier Plate consideration was made to build the DP in such a way that these temperature differences would be evened out. One way to do that was to weld square tubes to the inside of the drier. In this way channels were formed on the inside and between these tubes where the water could flow in a snake-like, zigzag pattern from the inlet to the outlet of the DP (as seen in Figure 13). The goal with this design was to reduce the temperature difference between the top and the bottom of the DP, and to reduce the risk for pools of stagnant cold water in the corners of the Drier Plate.

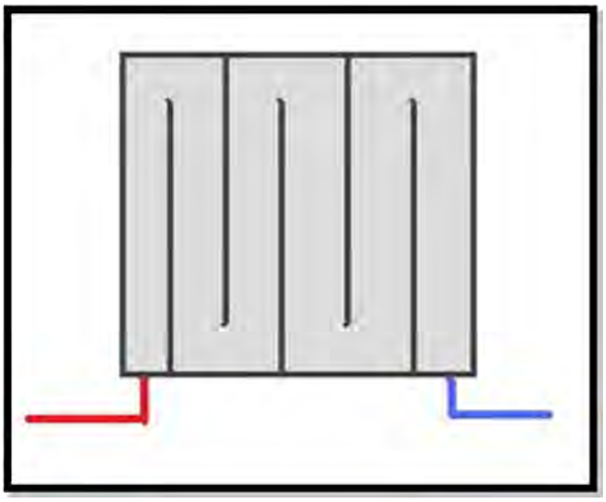

FIGURE 13 EARLY DRAWING OF THE CHANNELS INSIDE THE DRIER PLATE

This first DP aimed at drying a single paper as even as possible, but if successful this could be developed further in a coming setup to distribute the heat evenly over several papers. But in the end the benefit would be the same, to increase the quality of the paper by drying the papers as evenly as possible.

paper with values for a bare drier without papers.

3.2.2 MAKING A THINNER DRIER

As mentioned above in section 3.1.3 System C, the Drier Plate in this setup can be made thinner compared to the old system. That is because there is no benefit to have more water inside the drier than needed to deliver the energy required to dry the paper. A benefit of this is that as the DP is designed to lose energy, all energy stored in the water inside the Drier at nightfall – will be lost over night. If the Drier contains a lot of water – all that water would need to heat up in the morning before drying can start.

Taking this into account when determining the size of the DP, three parameters came out as limiting factors:

1. The height of a paper
2. The width of a paper and
3. The smallest size available for usable square tube in the local market.

The surface area had to be bigger than the biggest paper that needed to be dried, and was therefore decided to 90 x 60 cm. After visiting the local market square tubes in the size of 5 x 5 cm were bought and the depth of the DP was set to 5 cm. This meant that the Drier Plate would contain about 27 liters of water (also about 27 kg) and the steel in the DP (weighted after construction) weighted about 19 kg. That meant that the complete Drier Plate would use the first 4875 kJ[1] obtained from the sun, just to heat the water and steel from 20° to 60°C every morning. This can naturally seem like a big waste, but to put the figure in perspective it is about the same amount of energy required to produce steam from 2 kg of water, or about 7% of the daily energy input hitting a 5 m^2 collector in Bangladesh during December

[1] Energy stored in the DP = ($C_{p,water}$*kg_{water} + $C_{p,steel}$*kg_{steel})*ΔT

(which is the month with the lowest solar irradiance). This energy will also be useful as a buffer of energy inside the DP, as the hot water will enter the DP at one place, the water inside the DP will help to even out the temperature a bit. If the DP would be heated to 95°C and no new energy would be added, it would in theory be able to dry 8 papers using only the stored energy inside the DP (assuming one paper on average contains 0.45 kg of water that need to be evaporated).

When optimizing this "buffer" – the startup time in the morning (reason to reduce the buffer) needs to be weighed against the expected simultaneous energy extraction (i.e. the amount of papers being dried simultaneously on the same drier), as the water will cool down when passing a paper. The more papers that need to be dried at the same time the better it would be to increase the buffer. But there will be an energy buffer in the water inside the collector as well (where the size of that buffer depends on the collector used). Therefore, it is also possible to reduce the heat drop over the Drier Plate by increasing the flow rate of the water (for more details see section 3.4.1 Choosing a pump). Thus the optimal situation would be to make the DP as thin as possible and then adjust the flow rate to add more energy from the collector when needed.

3.3 CHOOSING A SOLAR COLLECTOR

As mentioned in section 1.5.2 Solar irradiation available in Bangladesh a concentrating collector would not be the best option for this application, partly because of the higher price for concentrating collectors, but mostly because of the low percentage of direct versus diffuse sunlight. After making this choice there are still two different technologies to choose between:

- Flat plate collectors
- Vacuum tube collectors

3.3.1 FLAT PLATE COLLECTORS

Traditionally some variant of a flat plate collector has been the standard for non-concentrating solar collectors and therefore this technology is one of the most developed in the world for solar thermal systems. With better insulation and new selective materials (that absorb a lot of the light coming from the sun but at the same time emit almost no photons in the infrared spectrum) these collectors can be very efficient and useful in many applications.

Using the most efficient collectors available could be beneficial in Bangladesh in the future because of the limited access to land that then will limit the available area from which solar energy can be collected. But for a start, the initial cost is a much more important parameter and with this high quality comes a high price. As an example, a standard flat plate collector in Sweden with an absorber area of 4 m^2 cost 18500 SEK (or 222,890[m] Tk) excluding VAT in late 2011 (SVESOL, 2011), corresponding to 6 yearly incomes for an normal worker in Bangladesh. But then many collectors in North America, Australia and Europe are made with anti-freezing protections to enable the use of the collectors even when ambient temperatures drops below 0°C. This has

[m] Calculated with an exchange rate of 1 Tk (also called BDT) = 0.083 SEK (on January 3, 2012).

historically been an important improvement for the solar industry (Butti & Perlin, 1981) but in most areas of Bangladesh the ambient temperature never falls below 0°C making an anti-freeze protection obsolete.

There are also cheaper versions of flat plate collectors available that do not have anti-freeze protection, and also collectors that only have a single or no glass cover to reduce the price. But a drawback with all flat plate collectors is that they are usually designed to contain very little water in order to make that water heat up faster and to a higher temperature. But the drawback is that they then need an external water tank for storage of the hot water.

3.3.2 VACUUM TUBE COLLECTORS

The other technology available is solar vacuum tube collectors. An affordable water-in-glass collector produced in China, has recently been introduced on the Bengali market. In late 2010 the cost for a full 50-tube collector with an absorbing area of 4 m^2 was only $240 (Sunsurf, 2010), which translates to 19,680 Tk. This price is about one tenth of the price for the flat plate collector mentioned earlier.

Water-in-glass collectors are one type of solar vacuum tube collectors where the heat transfer medium is water. For the collector to be functional, the tubes are filled with water and then inserted in a storage tank (also called the manifold) at some angle. The angle of the tubes increases the effect of the natural convection of the water inside the system. The absorbing area of these collectors consists of two glass-tubes with a vacuum between. The innermost tube is blackened to absorb the photons from the sun, while the vacuum between the two glass-tubes acts like a thermos keeping the hot water inside insulated from the surrounding air. The heated water in the vacuum tubes gains buoyancy and rises upwards due to natural convection into the manifold where it is stored for later use. Depending on the amount of tubes connected to one manifold the collector is mounted in a T (with the manifold on the top) or as an H rotated 90° (with the manifold mounted in the middle, as seen in Figure 14). These collectors are therefore called T-type and H-type collectors.

FIGURE 14: H-TYPE COLLECTOR AT MCC'S RESEARCH CENTER IN BOGRA.

The biggest drawback of a water-in-glass collector is that it does not absorb as big part of the incoming solar energy as a high-end flat plate collector would do. But with the lower losses and a much cheaper prize they are still a very interesting alternative. In Journal of Power Technologies an article compared the two types of collectors. The general conclusion was that the flat plate collector had higher losses, but a better value for the transmission and absorption, thus being able to absorb more of the incoming energy but not as good at storing the energy after absorption (Pluta, 2011). In a paper from the School of Mechanical and Manufacturing Engineering at a university in Sydney, Australia, the heat losses from a T-type water-in-glass collector was calculated. The result shows a loss of about 1.5 W/°K for the manifold and (depending on the quality) 0.5-0.9 W/°K • m^2 of the tubes (Budihardjo*, et al., 2002). This could be an interesting parameter to investigate as the drier is designed to contain very little water – the only possible storage of heat (if at all possible) would be inside the collector. Choosing a collector with low heat losses could therefore be very beneficial.

Another drawback is the dependency of import from China to get spare parts and additional collectors, as there is no production of similar collectors in Bangladesh. Local craftsmen are likely to be able to manufacture a bracket and maybe even the manifold in the future. But the vacuum tubes will require a specialized factory for production even in the future. On the other hand, the tubes are not likely to be hard to obtain in the future and the cost of the tubes is actually a very small part of the whole system. With the high production level of these tubes, the cost for a single tube is likely to stay below $3 (about 250 Tk) in Bangladesh.

3.3.3 CHOOSING THE SIZE OF COLLECTOR

After comparing the two types of collectors with each other it was quite clear that the water-in-tube collector would be ideal for this application in all aspects except one. It will take a long time to heat it up in the mornings. Therefore consideration had to be made to choose the right size of the collector. To start with the expected energy produced from the collector was of highest interest. Using the average value for the daily solar radiation in Bogra for January and February, the collector is expected to deliver 4.4 kWh/m^2 and day (or 15.8 MJ/m^2 and day) (SWERA, 1987-2000). But no collector can convert all incoming solar radiation into useful heat due to optical and thermal losses, and therefore the assumption was made that the collector would be able to convert about 70% of the incoming energy to useful heat (thus delivering about 11.0 MJ/m^2 and day).

From visits to two different paper production centers, D. Thomas managed to gather data regarding the weight of papers before and after drying, and then he calculated that on average a paper contains about 452 g of water. He also got some data about how much wood that was used at the center each day. Information regarding fuel consumption and amount of papers produced over a year was then obtained from Mr Swapan CEO at Prokritee. These data have been used together with the data that D. Thomas gathered to estimate that the center produces about 215 papers per day and that the center thus evaporates about 97 kg of water each day. Using the data gathered at the site, D. Thomas then estimated that the drier used about 8 MJ/kg water evaporated. As mentioned before this is not a very efficient level due to leakages and other inefficiencies and can be compared to 2.6

MJ/kg water, that is the theoretical minimum energy needed to evaporate 1 kg of water from 10°C to steam.

Looking at the collector again, each vacuum tube has an aperture area of 0.1 m^2 so using the assumption that the collector can produce about 11 MJ/m^2 and day, each tube is expected to produce about 1.1 MJ/day. To evaporate all the 97 kg of water using solar heat and with the assumption that the new system also would require 8 MJ/kg water evaporated would then require a collector with an aperture area of about 70 m^2. Even if using an optimal efficiency of the system with 100% conversion of the solar radiation and a system efficiency of 2.6 MJ/kg water evaporated – the aperture area would still need to be 23.3 m^2. Assuming that the new drying system would be more efficient than the old system, but not an ideal system, 5 MJ/kg water was chosen as the assumed conversion efficiency in the new system. It was also decided to buy a collector that in a future test could replace a smaller (8ft.) drier even if that collector would be slightly over-sized for this setup. Using these requirements and the estimation that a small drier use about 40% less energy per day compared to a big (16ft.) drier – a collector with the aperture area of 6.6 m^2 would be needed. The drawback of choosing a too big collector could be that it would take longer to heat the water in the morning, but as the buoyant hotter water always floats to the top – extraction of enough hot water to heat up the Drier Plate can start before the whole collector is hot

As the goal of the project was only to prove the concept, it had been possible to use an even smaller collector. But considering the big need of finding an alternative energy source for drying papers at the centers and the possibility to use a bigger collector for coming tests at bigger scale, it was agreed that the most reasonable thing to do was to buy a bigger collector from the start. This was also due to the low price of this type of collector and that 50 tubes (with a total aperture area of 5 m^2) already were available at the site in Bogra. Therefore a H-type collector designed to be connected to 50 tubes and then containing 210 liters of water was chosen.

3.3.4 HIGHEST TEMPERATURE IN THE SYSTEM

As the system was designed to circulate water and not steam, the maximum temperature in the hot part of the loop had to be less than 100 °C. Because the Drier Plate was designed to remove as much heat as possible from the water to the papers, it acts like a heat sink and reduces the temperature of the water. Thus the part of the loop stretching from the collector to the DP is regarded the hot side of the loop and the part "downstream" from the DP back to the collector is regarded the cold side. The max temperature on the hot side was then set to 95°C and the max temperature on the cold side was later defined by equipment included in the loop.

Again using the average value for the daily solar radiation in Bogra for January and February – a collector of 5 m^2 is expected to deliver 55.3 MJ/day assuming that 70% of the energy can be converted into useful heat, (SWERA, 1987-2000). To heat the whole collector from 10° to 95°C would require almost 75 MJ of energy, but as the hotter water floats to the top, temperatures above 95°C could be reached even if not the entire collector is that hot. As the hottest water will be circulated through the DP all the time, the expectation was that this maximum temperature would not be reached during these initial experiments unless the pump would be turned off for a longer period. If the DP would not be able to reduce the heat enough to keep these temperature limits another heat sink will be connected between the DP and the next component in the loop. The masses used to calculate the thermal storage possible in the system has been considered to be 210 kg water in the collector, 27 kg water in the DP and finally 19 kg steel in the DP. Thus at least 10 extra MJ will be stored in the DP before any water will reach the boiling point. Of course some heat will be stored in the other parts of the construction as well, but compared to the parts mentioned above they were regarded negligible for this test.

3.3.5 EXPECTED STARTUP TIME OF THE SYSTEM

To calculate the startup time in advance was very tricky as it depends on the irradiance in the morning (that naturally is lower compared to the average value of a full day), as well as on how fast the heated water moves from the vacuum tubes into the manifold. Once in the manifold the water stops heating – so a fast water-flow into the manifold would result in a more even temperature in the collector and consequently a slower heat up in the morning. While a lower water-flow gives the water more time to become hot and thereby help creating a layer of hot water in the top of the manifold that could be used to heat up the DP. In section 3.2.2 Making a thinner Drier it is stated that 4875 kJ or about 4.9 MJ would be needed to heat the Drier Plate from 20° to 60°C, where drying is expected to be comparable with the current driers. This is a small amount of energy compared to the total expected energy produced over a full day, but will further delay the startup time. The maximum energy delivered from the system is therefore expected to be in the afternoon, sometime after the sun has reached its highest point in the sky.

3.4 DESIGNING THE FULL SYSTEM

After choosing the heat carrier, a sketch was made of how the Drier Plate will look like and choosing a Solar Collector it was time to find the other equipment needed to run and monitor the system. As this equipment was expected to be more heat sensitive then the DP, it was placed in the cold loop to allow the Drier Plate to heat up as much as possible without harming the other equipment used. A schematic picture of the full system is seen in Figure 15.

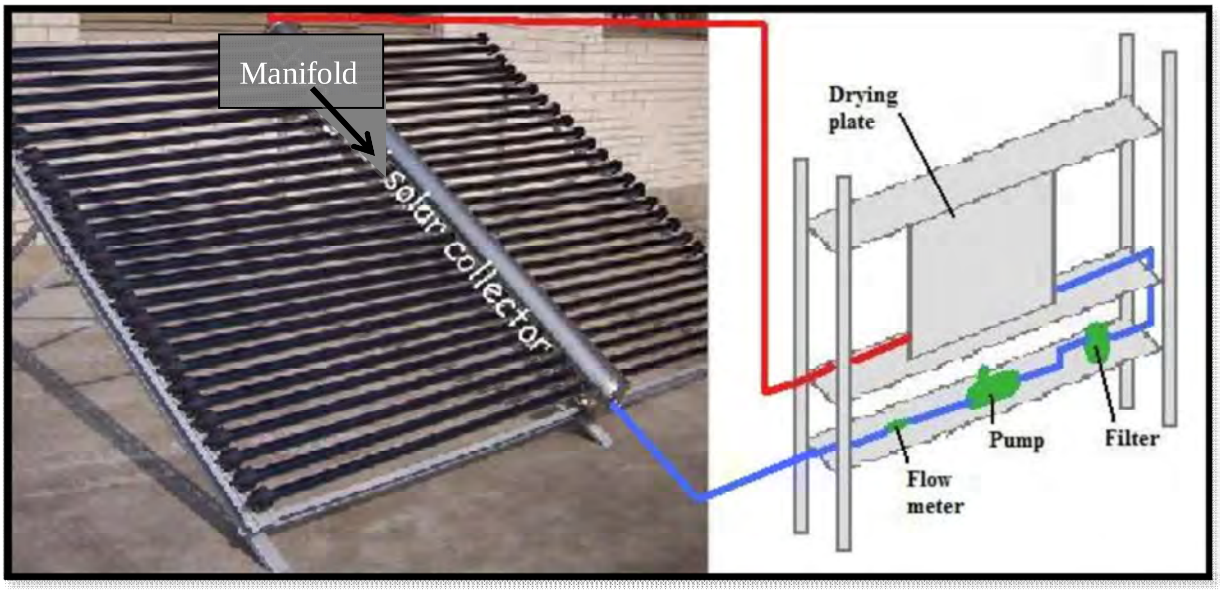

FIGURE 15 A SCHEMATIC PICTURE OF THE EXPECTED FULL SYSTEM.

The most important equipment in the system was:

1. A pump to circulate the water
2. A filter to make sure no damaging particles (such as those caused by corrosion) entered the pump
3. Water tank to continuously refill the system if water leak out.
4. Measuring equipment to measure temperatures and the flow rate

3.4.1 CHOOSING A PUMP

As the new system is very dependent on having a reliable pump to work, at first a new pump was obtained from the USA. The goal then was to find a pump that used a very small amount of electricity and that would be small to make it easy to import to Bangladesh. In the end this turned out not to be the ideal pump after all, and therefore a magnetic drive pump available at the research center in Bogra (seen in Figure 16) was used instead. If needed a similar pump would be possible to attain locally even if it most likely would have been imported as well. The choice of pump was important because it set the limitation for two important criteria:

1. The water temperature in the system could not reach a higher temperature than the limitation of the pump.
2. The flow rate had to be big enough to achieve a fairly even temperature distribution in the Drier Plate. This limited the pressure in the system and thus how big water head that could be allowed.

From the product specification the information was obtained that the pump could be used to pump water up to 93.3°C or 200°F (Little Giant Pump Co., n.d.). As the pump was positioned on the cold side of the loop, it was not considered likely that the pump would have a problem with too high water temperature. From the product specification a chart showing the correlation between the flow rate and the pressure inside the system was used (as can be seen in Figure 16). This chart showed that with a flow rate of 5 liter/min, the pump could pump the water to a height of 3 m.

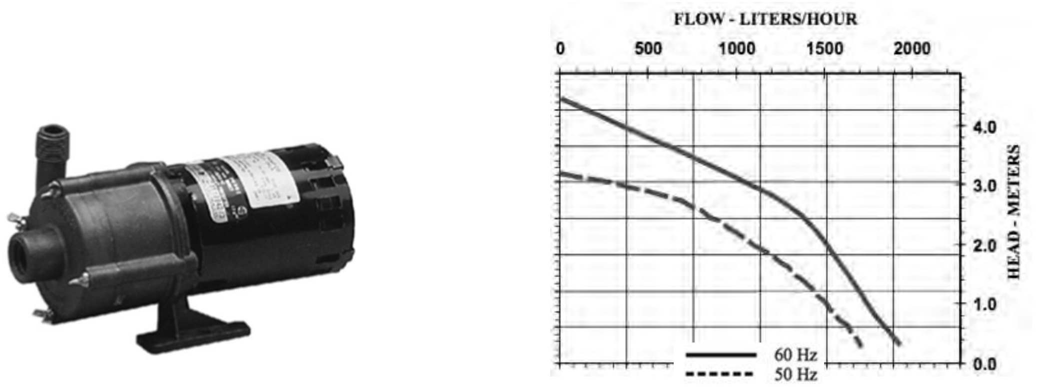

FIGURE 16 *LEFT*: IMAGE OF THE PUMP USED. *RIGHT*: A CHART OF THE FLOW RATE AS A FUNCTION OF THE PRESSURE IN THE SYSTEM. A FLOW RATE OF 2.4 L/MIN EQUALS A PRESSURE HEAD OF 3.1 M (50 HZ). (LITTLE GIANT PUMP CO., N.D.)

Depending on what structure the collector will be mounted on later, another pump might be needed for the final system, but for the initial experiments this was more than enough, as the collector could be mounted on the ground during this phase and the DP would not have any part higher than about 2 m. But the pressure in the system also depends to some degree on the length and the diameter of the tubes as well as on the pressure drop in the flow meter used. Therefore the flow cannot be read exactly from this chart, but a flow rate of 3 m/s was assumed in the initial calculations. This would result in changing the water in the Drier Plate on average every 9 minute. To ensure stable drying conditions the flow rate had to be big enough to deliver more energy than were used to dry the papers as long as hot water was available in the collector. Averaging 10 papers being dried during a working day (assumed to be 9 hours) each paper had to dry in less than 54 min. To evaporate 0.45 kg of water in 50 min, assuming an energy need of 5 MJ/kg would require that 2.5 MJ/hour or 0.04 MJ/min can be extracted from the Drier Plate continuously. The pump thus has to add, at least that much energy to the DP during the same time. Assuming a minimum temperature of 50°C in the DP during drying, the total stored energy in the Drier Plate would then be at least 6.1 MJ. Assuming that the collector continuously supplied water of 50°C and the pump would replace all water in the DP every 9 min, the energy flow could be as high as 40.7 MJ/min if the water leaving the Drier at the same time would be 0°C. But in reality this value would be much, much smaller. The limiting factor here is clearly not the flow rate, but rather how long time of the day the collector can supply water above 50°C.

3.4.2 CHOOSING A FILTER

To make sure that no big particles, such as corrosion from the DP and other metal parts that could damage the pump and flow meter circulated in the water, a filter had also to be added to the loop. Unfortunately, no filter made for hot water was found in either Bogra or Dhaka, so a filter for drinking water was bought in Dhaka and all tubes changed to more heat resistant ones. This worked well as the main component of the filter was made of more heat resistant material than the inlet and outlet tubes and connections.

3.4.3 ADDING A WATER TANK

Another important part of the system was the water tank added on a separate loop to keep the air out of the system. The idea was that this tank would always be full with water and placed at a height in order to create a slight overpressure inside the system. So if any leakage would occur the water would flow out of the system instead of air entering into the system. The tank would then be connected to the cold water inlet of the solar collector. By adding this tank any water leaking out from the system would be replaced with water from the tank and by connecting the tank to the coldest point in the system (and by being on a separate loop) the water in the tank could stay cold while the rest of the system heated up, thus reducing the heat losses from the system.

3.4.4 MEASUREMENT EQUIPMENT NEEDED

In order to evaluate the performance of the system and to answer the research questions of the project, a lot of measuring equipment needed to be integrated in the setup.

3.4.4.1 FLOW METER

One important parameter to measure was the flow of the water that circulated in the system, as the exact flow is important to calculate the energy flow in the system. To achieve this, a flow meter chosen that had an accuracy of ±2% and a repeatability of ±0.5%. The flow meter did not have any problem with the flow rate intended as it could measure flows between 0.76 and 15.1 liter per minute but it could only be used for water temperatures below 80°C and was therefore pushing down the max temperature allowed in the cold side of the loop to 75-78°C.

3.4.4.2 TEMPERATURE, HUMIDITY AND RADIATION SENSORS

To obtain data of good quality, some measurement equipment had to be imported but as this equipment only was used to prove the concept this was not seen as creating a long-term dependency on imports. A data logger had previously been imported from the USA and was used in the setup to collect data over several days, and from several instruments at the same time. This was a crucial piece of equipment for obtaining the high level of detail in the data recorded from the experiments. Some of the most important data were: the temperature at different points on the drying surface of the Drier, the temperature of the water circulating in the system as well as the ambient temperature. The ambient relative humidity (also called ambient RH) as well as the RH at a point 10 cm above the DP and finally two pyrometers were used to measure the solar radiation during the tests using the Solar Collector. A more extensive list of the diagnostics equipment used can be found below:

- One CR10X Datalogger from Campbell Scientific
  - 1 for Measurement and Control
    - Accuracy: 0.05% of the full scale reading
    - A/D bits: 13
    - Resolution: 0.33 µV
- Fourteen T-type thermocouples
  - 9 for measuring the surface temperature on the DP
  - 5 to measure water temperature inside the collector
    - Accuracy: 0.5°C
- One K-type thermocouple
  - 1 for regulating the temperature of water leaving the EWH
    - Accuracy: 1°C
- Five Thermistors
  - 2 for measuring water temperature in to and out from the heat source currently used
  - 2 for water temperature in to and out from the DP

    - 1 for measuring the ambient air temperature
        - 44036RC Precision Epoxy NTC Thermistor Accuracy: 0.1°C
- Two Humidity sensors
    - 1 for ambient humidity
    - 1 for measuring the humidity 10 cm above the DP
        - Ambient humidity and one of the sensors above the DP:
            - Accuracy: ±3.5%
            - Repeatability : ±0.5%
- Two pyrometers
    - 1 for direct light
    - 1 for diffuse light
        - Both pyrometers were of the same type with accuracy between ±1% to ±5% depending on the angle of the incoming light. The repeatability was ±1%.
- One Shade ring
    - To prevent the direct sun light from reaching one of the pyrometers

4 CONSTRUCTING THE NEW DRYING SYSTEM

After designing the system it is time to build it all. This chapter covers the steps taken to manufacture and construct the system as a whole. It also introduces some new components that were not included in the initial design such as an electric water heater.

Finally the chapter covers the various measurement equipment that were used as well as some early tests that were used to fine-tune the setup and regulation of the system.

4.1 OVERALL PROGRESS

After completing the design of the new system – it was time to actually build it. The construction of the new drier system took place at the center for development of sustainable technology outside of Bogra (owned by MCC), where the initial setup-phase took over a week as M. Hjort had never built a similar system before and, therefore, a complete list of all materials needed could not be given from start. Also, more tubes, tube insulations, valves and fittings for the tubes and the other equipment had to be bought by MCC staff because M. Hjort could not speak Bengali.

4.1.1 INTEGRATING THE PUMP, FLOW METER AND FILTER

The first step was to put together a small loop with just the pump, the filter, and a visual flow meter (seen in Figure 17) that pumped the water: from a bucket, through the loop, and then back to the same bucket, primarily to make sure that the pump worked, that the filter worked with the new fittings and that the piping was watertight.

The reason to start with a visual flow meter was to protect the sensitive electrical flow meter in case the filter would not hold for the hot water when the heat source would be connected to the loop. Also the electrical flow meter needed to be connected to a data logger to turn the electrical signal into a readable value, so it was not useful until the data logger was introduced.

As for the temperature measurements, they were all made with the same IR thermometer that had been used when visiting the Shuktara center in Feni as it was very mobile and easy to use. But as mentioned in section 3.2.1 Reducing the variation in surface temperature, the IR thermometer seems to give a too low values when aimed at reflective surfaces such as metal plates. Therefor it was also replaced when the data logger was connected to the system.

FIGURE 17 PUMP, FILTER AND VISUAL FLOW METER.

4.1.2 THE NEED FOR AN ELECTRIC WATER HEATER

The next step was to connect the heat source but as it took several weeks to import the Solar Collector from China, an alternative heat source needed to be used in the initial setup and later also in the first phase of the tests. A big part of the experimentation was therefore conducted without the actual solar collector; instead a 1200 W Electric Water Heater seen in Figure 21 (also called the EWH for short) was used as the heat source. The empty heater weighed 16.8 kg and it could contain about 29 kg of water.

A benefit of the situation was that the system needed to be built in order to easily exchange the heat source once the solar collector arrived, which resulted in a big flexibility in the system. In future designs, this flexibility could be used to integrate more than one heat source and thereby enabling use of auxiliary heating on cloudy days. The auxiliary heat could also be used to heat up the driers if there would be a need to dry papers in the morning before the solar collector had started to produce enough heat on its own. The EWH was well insulated as it was designed to produce hot water for domestic usage and could therefore keep some hot water over night. That reduced the startup time the following morning as well as the losses during the day. The increased dependence on electricity was not regarded as a big problem as a pump already was depending on electricity to circulate the water. But even if it was ok that the EWH turned off at a power blackout – it was a bigger problem that the pump and the measurement equipment stopped working. To handle this an UPS connected to a 12 V car battery was included in the setup (see section 4.4.1 Need of backup electricity for more detailed information). This stopped data from being lost as it provided backup electricity to the measurement equipment and the pump, but not until the solar collector had replaced the EWH, did the system become independent of the power shortages. But just as a cloud can pass the sun for a while, the drying could continue even when the EWH was not operational.

The next step in constructing the system was therefore to build the Drier Plate.

4.2 BUILDING THE DRIER PLATE

As agreed with MCC and Prokiree, the steel for the drier was obtained locally and local craftsmen made all construction work that could not be made by M. Hjort. There were several reasons not to use stainless steel in this construction. One reason was that the material would be more expensive and another that this drier would only be used for a limited period testing the first design. Using stainless steel would also require more specialized welding and a very good welder from MCC's job creation program could help building the drier if ordinary steel was used. Finally the water in the DP will flow in a closed loop between the collector and the DP and then back again, thus ideally no new oxygen would be added to the loop. This reduces the benefit of using stainless steel in the drier compared to the old system, where new oxygen constantly could enter a drier through the pressure-release hole as well as through cracks around the boiling-tray.

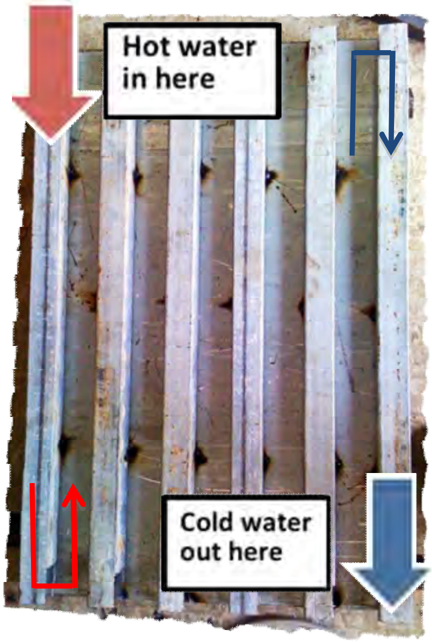

FIGURE 18 SHOWING THE CHANNELS AND TUBES INSIDE THE DRYER PLATE (VERTICAL SETUP) PICTURE MIRRORED TO MATCH THE PLACEMENT OF THE INLET AND OPUTLET WITH FIGURE 3.

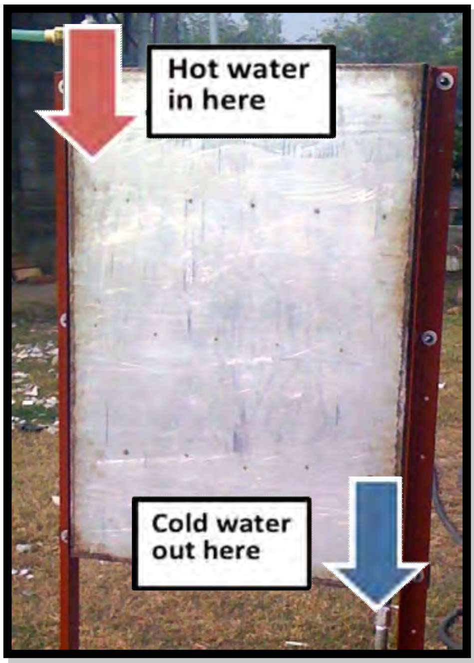

FIGURE 19 "FRONT SIDE" OF THE DRIER PLATE

When starting to build the DP, the square tubes were easily spot-welded to the inside of one drying surface (the surface called the front side, as seen in Figure 18). The hot water would then enter the Drier Plate in the top left corner (as seen in Figure 19[n]) and continue down inside the first tube. Each tube had an opening on the top "left" side, and another one in the bottom "right" side to let water flow down one tube, up through a channel and then back down again through another tube. This up-down movement of the water continued until the water left the DP through the last tube.

The next step in the construction was much harder – in order to weld the opposite surface (i.e. the back side) onto the tubes, eight holes were drilled in the new steel sheet at positions that would be covered by a tube. This way the tubes could be fastened to both of the surfaces to minimize the amount of water that would pass between the steel sheets and the tubes. Unfortunately this did not work as planned, and the DP had to be taken to a local craftsman that could use gas welding (seen in Figure 20) to get the holes watertight.

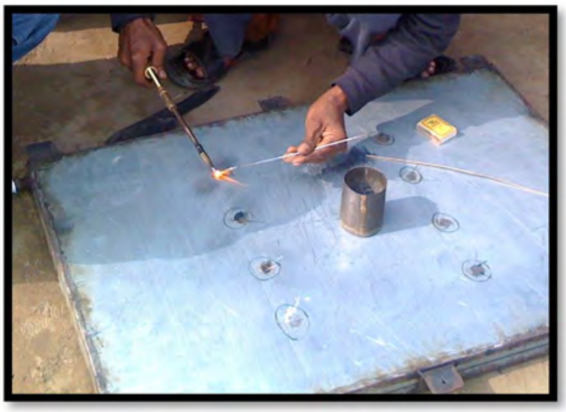

FIGURE 20 "BACKSIDE" OF THE DRIER PLATE HAD TO BE GAS-WELDED TO BECOME WATERTIGHT.

The end result was usable for the experiments but rendered the backside practically useless for drying because the eight big spots where severely misshaped and had different thermal properties compared to the rest of the drier. In future designs the channel-creating elements will probably only be fixed to one side, increasing the risk of hot water flowing around and perpendicular to the channels, instead of following them. But even if this would increase the temperature difference between the top and the bottom of the Drier Plate, the effect will likely not be big enough to justify the extra work trying to fix the channels on both sides.

[n] Note that the image in Figure 18 is mirrored to make it look like a cut-through of the drier shown in Figure 19. The surface shown in Figure 18 is actually the inside of the front surface shown in Figure 19, not the "backside" of the Drier Plate.

4.3 RECORDING DATA WITH A DATA LOGGER

After connecting the Drier Plate to the loop, the next step was to start to monitor the system more systematically. To do that a data logger had to be introduced to the system. Initially only simpler tools, such as a hand-held IR thermometer and a visual flow meter had been used. But once the reliability of the measurements became of interest and the need to record many different types of data at the same time increased, the data logger had to be included in the setup. As the experiments developed also new measurements were added to the data logger, but as long as the electricity was available it performed above all expectations, and many of the experiments in this study would not have been possible without the use of this device. The data logger could log data on a second-basis but as this was not needed in this study all measurements were logged as the average of the data recorded each 1 min.

4.4 MEASURING THE TEMPERATURE OF THE SYSTEM

To measure the temperature in the system two types of equipment were used: thermocouples and thermistors. Four of the thermistors were inserted in the inlet and outlet of both the DP and the EWH (these were later moved to the SC) to measure the water temperature at these four points (as seen in Figure 21). A fifth thermistor was then placed inside a plastic cylinder with holes drilled through it in order to measure the ambient temperature (as seen in Figure 24).

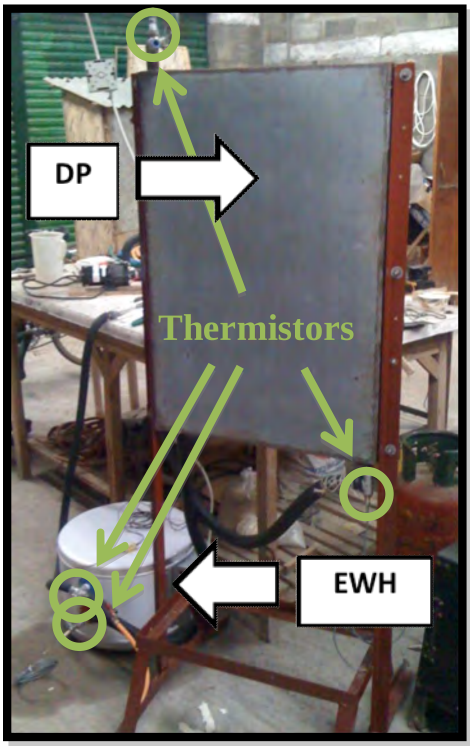

FIGURE 21 FULLY BUILT DRIER PLATE (DP) AND THE ELECTRICAL WATER HEATER (EWH) USED FOR SOME TESTS.

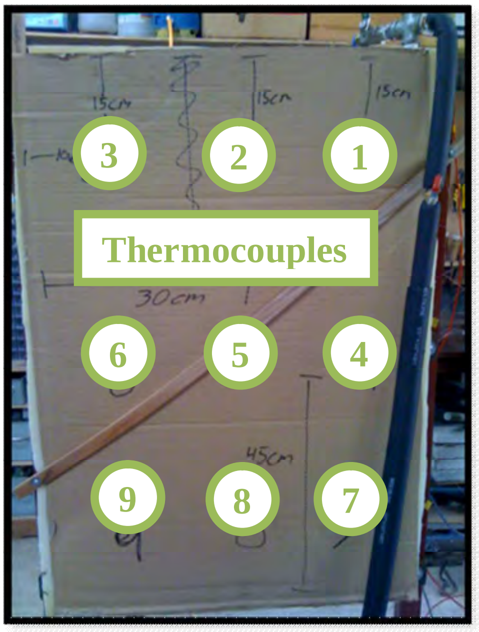

FIGURE 22 INDICATIONS ON WHERE THE NINE THERMOCOUPLES WERE PLACED IN FINAL SETUP – SEEN FROM THE “BACKSIDE” OF THE DP.

In order to rely not only on the water temperature, a set of nine thermocouples (also called TCs) was positioned on the surface of the Drier Plate to record the temperature distribution on the surface of the DP. The TCs were placed on an imaginary grid, sized 40x60 cm (seen in Figure 22). The top row of three TCs was placed 15 cm from the top and 10 cm from the left and right side of the DP. The bottom row mirrored this and was placed 15 cm from the bottom and 10 cm from the left and right side. The middle row was then 45 cm from both the top and bottom. All the positions were then numbered 1 to 9, where 1 was placed closest to the hot inlet (seen from the back side, that is in the top right corner) and position 9 was placed closest to the cold outlet (in the bottom left corner).

4.4.1 NEED OF BACKUP ELECTRICITY

During the first day of drying, 13 papers were dried but in the same time the power went off for a total of two hours, divided into four occasions and interrupting three ongoing drying tests. The three tests had to be discarded due to missing data as well as interruption in the water flow and heat generation. To solve this problem a UPS connected to a 12 V car battery was obtained. In the setup using the electric water heater as heat source the UPS was only connected to the data logger as the most important function was to monitor the setup, and it was unclear if the UPS could power the EWH on its own for several hours. But in the setup using the solar collector as the heat source the pump was also connected to the UPS. After several days of testing, it was clear that the battery had more then enough energy stored to drive both the pump and the data logger during all the power cuts that occurred after its installation. This was an important proof of concept as constant access to electricity is crucial to circulate the heat obtained from the sun in the new system design.

4.4.2 RELATIVE HUMIDITY MEASUREMENTS

After connecting all components and measuring equipment (including the electric flow meter and the water tank) a decision was made to start the initial drying tests inside the workshop where electricity and tools were close at hand and all things could be left over night without risk of damage or theft. This was also thought to resemble the final drying conditions better than testing in the open air, as all dryers in the centers are placed under a roof. The workshop had one big port that was usually rolled up during the daytime but not always fully opened, but on the other hand the workshop had plenty of air up to the ceiling, so there was no risk of trapping so much humidity inside the workshop that drying efficiency would be reduced. To measure this build up and more importantly, to log the natural change in humidity over a day, two sensors were used. One measured the ambient relative humidity, and the other one was placed 10 cm above the drier Plate (as seen in Figure 23) to measure the relative humidity at this point. To get the correct value, the data had to be correlated with the ambient temperature, and both the ambient temperature and ambient humidity should be measured without exposure to direct wind. Therefore these two sensors were placed inside a tube with holes and a rain protection lid on the back of the data logger (seen in Figure 24).

FIGURE 23 RELATIVE HUMIDITY MEASUREMENT 10 CM ABOVE THE DP.

FIGURE 24 TUBE FOR MEASURING AMBIENT RH AND AMBIENT TEMPERATURE.

The sensor above the DP was placed there in the hope that most of the water evaporated from the paper would flow upwards, and thus this value would be used to estimate how much water that evaporated per minute. But in the end these data have not been used in this report. Instead each paper was weighed before and after it was dried, and the time taken to dry the paper noted down. These figures were then used together with data about the temperature in the drier plate, to calculate the average energy used to dry the paper in MJ/kg water that had been evaporated from the paper.

4.5 INITIAL TESTS AND RE-DESIGN OF MEASUREMENT SETUP

The system was now ready to be tried as a whole and the early results could then be used to redesign the measurements to obtain more interesting results later on. After putting everything together, on the 19th of Jan 2011 it was finally time to start the EWH, the pump and the data logger to record some temperature data for the first time.

4.5.1 INTERNAL VS. EXTERNAL HEAT REGULATOR

After a full day of heating and circulating water in the system it was clear that the EWH could heat the water to 72.8°C before reaching the maximum temperature allowed by the internal heat regulator. During the first two days the EWH reached this cut-off temperature several times (as can be seen in Figure 25 below).

Afterwards the water temperature went down to 64.3°C before starting to rise again.

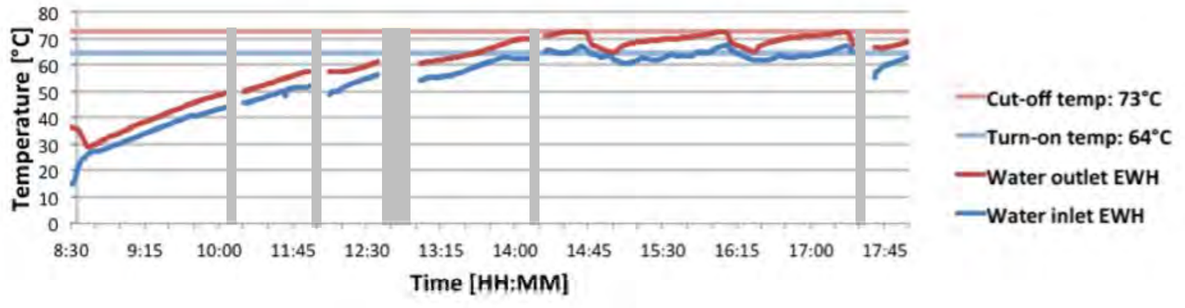

FIGURE 25 VARIATIONS IN OUTLET AND INLET TEMPERATURES OF THE ELECTRIC WATER HEATER DURING THE FIRST DAY OF DRYING PAPERS. THE PUMP WAS TURNED ON AT 08:26 AM ON THE 19TH JAN 2011. THE POWER WAS GONE AT FIVE OCCASIONS DURING THE DAY (MARKED WITH GREY VERTICAL RECTANGLES).

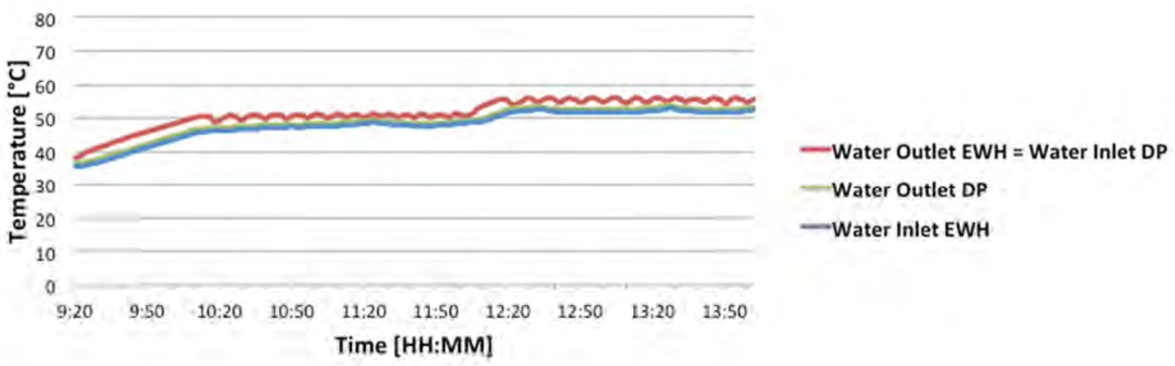

FIGURE 26 VARIATIONS IN OUTLET AND INLET TEMPERATURES OF THE ELECTRIC WATER HEATER AND THE DRIER PLATE. THE PUMP WAS TURNED ON AT 09:01 AM ON THE 27TH JAN 2011.

To reduce this variation an external heat regulator was introduced. With the external regulator the heat output varied less than 2°C (as seen in Figure 26). Sometimes this variations from the maximum to the minimum of one cycle, was as low as 1°C – so it was clear that the input temperature of the water was much more stable with the external regulator.

The drawback while using the external heat regulator was that the thermistor that measured the water temperature from the hot water outlet on the EWH, had to be changed to a K-type thermocouple to give the external regulator a useful signal. This meant that the data logger could not record these data any longer (as the logger was not programed to record this type of data).

Instead an assumption was made that the temperature of the water leaving the EWH could be regarded equal to the temperature of the water entering the DP. As this difference had never been bigger than 0.5°C during the first two days while using the internal heat regulator, this assumption was regarded reasonable.

4.5.2 USING THE TCS TO DETERMINE THE TEMPERATURE INSIDE THE DP

The next step was to look at the data from the TCs that had been placed on the back of the Drier Plate behind an insulating layer. As the backside was rendered useless for drying, this was regarded an interesting alternative use of that surface, as it was clear that the average temperature of all the nine thermocouples (shown in Figure 27 below) gave a very stable value for the temperature of the water inside the DP. Here it is also clear that the average temperature of the TCs is closer to the inlet temperature of the DP during steady state but lag behind during a longer period of increasing the temperature entering the drier plate.

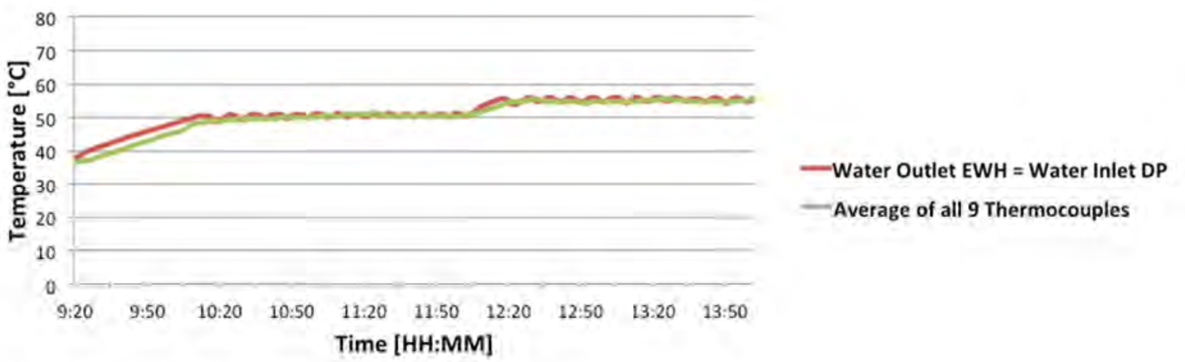

FIGURE 27 VARIATIONS IN WATER TEMPERATURE ENTERING THE DRIER PLATE COMPARED TO THE AVERAGE TEMPERATURE RECORDED BY THE 9 THERMOCOUPLES (TCS) PLACED ON THE BACK OF THE DP (ON THE 27TH JAN 2011).

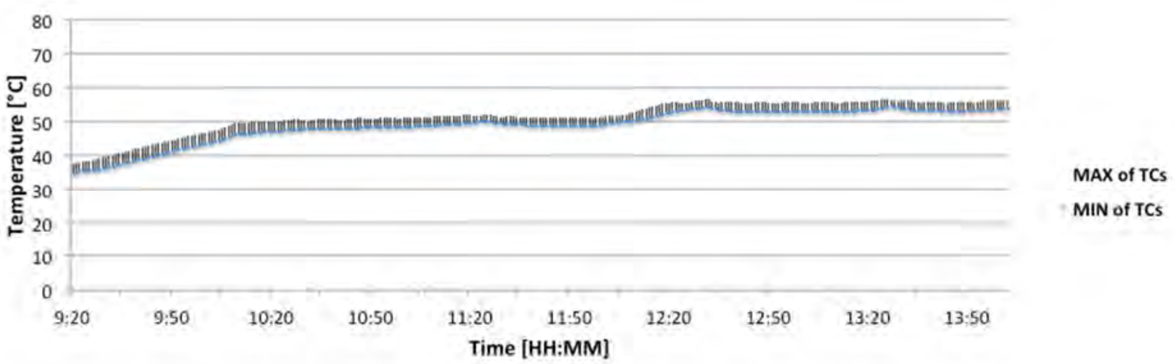

FIGURE 28 VARIATIONS IN TEMPERATURE RECORDED BY THE 9 THERMOCOUPLES (TCS) PLACED ON THE BACK OF THE DP. THE BLUE LINE SHOWS THE LOWEST TEMPERATURE RECORDED BY ANY OF THE TCS AND THE TOP OF THE GREY AREA SHOWS THE HIGHEST TEMPERATURE (ON THE 27TH JAN 2011).

Comparing this average temperature with the difference between the top and the bottom of the DP shown in Figure 28 above, it is clear that the difference never is bigger than 4°C. This can be compared with the 8°C temperature difference between the top and bottom of an 8 ft. drier at Shuktara center in Feni (as mentioned in section 3.2.1 Reducing the variation in surface temperature). From these early findings it was clear that the data from the TCs on the back could give some interesting information about both the average temperature inside the drier plate and about the temperature distribution inside the DP. But as will be seen later on, some interesting data can also be obtained from placing the TCs on the front of the DP, between the paper being dried and the steel surface. But to better understand what is happening when a paper is being dried it is good to first refresh some basics on how papers dry.

5 THEORETICAL BACKGROUND

This chapter summarizes the basics of how water is stored inside a paper and how it act when a paper is being dried. Also a short section on how to calculate the water content inside the paper is included, as well as a section describing both the equations used to calculate the energy extracted from the solar collector during a day, and the equations used to calculate the energy needed to dry a paper.

In the end the equations used to calculate the amount of solar irradiance that hit the collector can be found.

5.1 THEORETICAL BACKGROUND: TO DRY PAPERS

5.1.1 STRUCTURE AND POSITION OF WATER INSIDE A PAPER

Stig Stenström mentions in his book *Paper Chemistry and Technology* that wet paper is a mixture of three different materials. Firstly, the porous cellulose fibers can contain water (In Stenström's terminology this is water in the intra-fiber pores). Secondly, and thirdly are the liquid water as well as a gas mixture of air and water vapor that is located between the fibers (He calls these areas inter-fiber pores). Stenström also write that at ratios of 3-4 kg water/kg dry matter both the intra-fibers and most of the inter-fiber pores are saturated with water but the ratio of the liquid water inside the fibers, around the fibers and in the water-air mixture are not constant. As the paper dries, the water between the fibers evaporates and water from inside the fibers is pushed out as the fibers shrink. (Stenström, 2009)

This is also confirmed by Gunnar Gavelin who adds that the water in the inter-fiber pores is not connected as hard to the fibers as the water in the intra-fiber pores. Therefore the drying process is expected to be faster in the beginning and then slow down as more of the water that evaporates comes from the intra-fiber pores instead of the inter-fiber pores. Gavelin also mentions that if the drying process is very fast, the change of the fibers gets more important as it can cause the outer layers to dry and shrink before the water in the inner fibers start to evaporate. This increase the risk of trapping moisture inside the paper as it get harder for the water to be transported to the surface of the paper (Gavelin, 1999). One benefit of drying methods used in Bangladesh is that the temperatures are lower and the drying time is longer compared to conventional drying, thus reducing the risk of trapping moisture inside the papers.

5.1.2 THREE MAIN WAYS TO TRANSFER HEAT INSIDE A PAPER

In order to dry a sheet of paper it is important to take into account at least three different processes:

1. The thermal conductivity
2. The convection of free steam and liquid water inside the paper
3. The evaporation rate from the paper surface facing the surrounding air

As the paper dries, the importance of each process changes. First the water film between the drying surface and the paper evaporates which reduces the thermal heat transfer from the drying surface to the paper. The thermal conductivity between the DP and the paper will therefore be biggest in the beginning.

After that, the effect of free water in the paper that is evaporating and moving towards the surface of the paper facing away from the drier takes over. But as long as the average temperature in the paper is low enough and the thickness of the paper big enough, the steam will condense into water again, releasing a lot of energy to the fibers and free water around it. This process will heat new water that turns into steam and continues to travel towards the surface of the paper. Eventually this process, together with regular heat transfer in the water and fibers, will heat the water in the surface of the paper, which then will start to evaporate. After the temperature in the paper has increased enough, the steam can flow straight through the paper without condensing to water on the way, thus removing big amounts of water to the air in the form of steam. This is one of the most important processes in drying paper, as it is one of the fastest ways to remove water from the paper. (Gavelin, 1999)

5.1.3 OPTIMAL DRYING AND MOISTURE CONTENT IN THE PAPER

Finally Gavelin states that there is an optimal point beyond which continued drying will only use extra energy to no gain. This over-drying can even weaken the paper and make it more fragile. The background to this point of optimal drying is that when paper is stored, it will always exchange moisture with the surrounding air, until the relative humidity versus the amount of water in the paper reaches a balance (Gavelin, 1999). When this balance is reached depends on the temperature in the room, the type of fiber and the moisture in the air. If the paper is dried beyond this point it will take up water again as soon as the drying process stops, thus energy used to over-dry gets wasted. To evaluate this all papers were weighed after drying and compared with the weight of the same paper during storage conditions. This ratio was then calculated in the same way as the wet-based moisture content is usually defined, except that the mass of dry paper ($m_{Dry\ paper}$) was defined as the weight of the paper during storage conditions. As an exact value of the "dry weight of a paper" always is a question of definition, and no better way of determining the weight of a dry paper existed at the research center, this was considered a very good definition even if "storage conditions" could have been better defined. The moisture content was therefore defined as:

$$\boldsymbol{MC_{wb}} = \frac{\boldsymbol{m_{Water\ in\ Paper}}}{\boldsymbol{m_{Water\ in\ Paper}} + \boldsymbol{m_{Dry\ paper}}}$$

Equation 1

The mass of water that should be dried off ($m_{Water\ in\ paper}$) was calculated by subtracting the weight of the dry paper ($m_{Dry\ paper}$) from the weight of the wet paper ($m_{Wet\ paper}$) before drying (i.e. after soaking the paper in water). To reduce the amount of calculations needed, Equation 1 was therefore reformulated to use the weight of the wet paper ($m_{Wet\ paper}$) directly instead. The equation then turned into Equation 2:

$$\boldsymbol{MC_{wb}} = \frac{\boldsymbol{m_{Wet\ paper} - m_{Dry\ paper}}}{\boldsymbol{m_{Wet\ paper}}}$$

Equation 2

Finally the paper was weighed again after drying, where ideally the new weight of the paper after drying ($m_{Dried\ paper}$) should equal the weight of the same paper during storage conditions ($m_{Dry\ paper}$). To calculate a value for how close to the optimal drying each paper had got after drying, the Moisture Content was calculated again, but this time using the weight of the paper after drying (as seen in Equation 3 below).

$$\boldsymbol{MC_{wb,dried}} = \frac{\boldsymbol{m_{Dried\ paper} - m_{Dry\ paper}}}{\boldsymbol{m_{Dried\ paper}}}$$

Equation 3

If %$MC_{wb,dried}$ turns out to be positive, the paper is under-dried and should have been left longer on the Drier Plate, and if the value turns out negative, the paper is over-dried and should have been taken off earlier. While the optimal result is when the value equals zero as that mean that the paper was dried exactly to the level of the storage conditions.

5.1.3.1 CHAPTER DEFINITIONS:

MC_{wb}	Wet-basis Moisture Content before drying [%]
$MC_{wb,dried}$	Wet-basis Moisture Content after drying [%]
$m_{Water\ in\ Paper}$	Mass of water removed from the paper during the drying process [kg]
$m_{Dry\ paper}$	Weight of the paper during storage conditions [kg]
$m_{Wet\ paper}$	Weight of the paper after being soaked in water [kg]
$m_{Dried\ paper}$	Weight of the paper after drying [kg]

5.2 THEORETICAL BACKGROUND: DRYING PAPERS SOAKED IN WATER

To enable repeatability in the tests, the same paper was soaked in water and then re-dried several times. According to Gavelin this should not create any problem even if the fibers will shrink more the first time a paper is dried, compared to a paper that is re-moisturized and then dried again. This is because, he claims, repeating that cycle several times will not affect the paper significantly (Gavelin, 1999), so even if this might not have been exactly comparable with drying papers for the first time, at least the error was consistent. Though repeatability was interesting, the main reason for drying papers soaked in water instead of newly produced papers, was that the experimentation was conducted at the research center in Bogra and not at one of the centers producing papers. Newly produced papers in need of drying were therefore not available.

5.3 THEORETICAL BACKGROUND: ENERGY REQUIRED FOR DRYING

As the final goal of this report was not just to find out more about drying papers in general, but rather to find a new system to replace the old drying drums, it was important to look at how much energy that could be converted to hot water by the collector ($\boldsymbol{E_{Converted\ by\ Collector}}$). Another interesting parameter was how much energy that was used to dry a paper ($E_{Drying\ a\ paper}$) using the new system. As mentioned in 1.5.2 Solar irradiation available in Bangladesh, the expected energy delivered from the solar collector is tightly related to the incoming solar radiation. It can therefore be estimated by multiplying the average daily radiation per square meter and the aperture are of the collector. But as mentioned in section 3.3.3 Choosing the size of collector, not all of this energy will be converted into useful energy (in the form of hot water).

5.3.1 ENERGY CONVERTED TO HEAT IN THE COLLECTOR

To estimate the conversion efficiency of the collector, the irradiance was measured with pyrometers and the average value was logged on a minute-by-minute basis. The measured irradiance (W/m^2) was used to calculate the total solar irradiation (J/m^2) that hit the collector during each minute and could then be compared with the heat that was extracted from the collector. To compensate for the (in this setup) indefinable delay between the time when the solar irradiance hit the collector, and the time when the heated water passed the thermistor in the outflow from the collector, averages over longer times than one minute needed to be used. Therefore the total energy from the solar irradiation over a whole day ($E_{Total\ Solar\ Radiation}$) was compared to the energy that had been converted into heat inside the collector during the same time ($E_{Converted\ by\ Collector}$) as given by Equation 4 below:

$$\eta_{Collector} = \frac{E_{Converted\ by\ Collector}}{E_{Total\ Solar\ Radiation}}$$

Equation 4

To get the total amount of heat that was produced in the collector during a day, it was not enough to only calculate how much energy that had been extracted from the water in the collector ($E_{Extracted\ from\ Collector}$). The increase/decrease in the stored energy inside the collector ($\Delta E_{Stored\ in\ Collector}$) had to be determined as well, and the sum of the two then gives the total amount of energy that was converted into hot water, as shown in Equation 5 below:

$$E_{Converted\ by\ Collector} = E_{Extracted\ from\ Collector} + \Delta E_{Stored\ in\ Collector}$$

Equation 5

The energy extracted from the collector was then calculated using EQUATION 6 below:

$$E_{Extracted\ from\ Collector} = [E_{Outgoing\ from\ Collector} - E_{Incoming\ to\ Collector}] = \dot{m}_{Water} \cdot C_{P,Water} \cdot \Delta t_{Day} \cdot [T_{Outlet\ from\ Collector} - T_{Inlet\ to\ Collector}]$$

Equation 6

While the change in stored energy inside the collector was calculated using EQUATION 7 shown below. In this equation the energy stored in the material of the solar collector has not been taken into account, but as most of the collector was built by glass and insulating materials the energy stored in the SC has not given a very big contribution to this value.

$$\Delta E_{Stored\ in\ Collector} = m_{Water\ in\ Collector} \cdot C_{P,Water} \cdot (T_{Average\ of\ Collector\ in\ evening} - T_{Average\ of\ Collector\ in\ morning})$$

Equation 7

5.3.1.1 CHAPTER DEFINITIONS:

$\eta_{Collector}$ Efficiency in the collector [-]

$E_{Converted\ by\ Collector}$ Energy converted into heat by the collector during one day [MJ]

$E_{Total\ Solar\ Radiation}$ Total energy (solar irradiation) hitting the collector during a day [MJ]

$E_{Extracted\ from\ Collector}$ Energy extracted from the collector during one day [MJ]

$\Delta E_{Stored\ in\ Collector}$ Change in stored energy inside the collector during one day [MJ]

$\dot{m}_{Water}$ Mass flow rate of the water in the system [kg/min]

$m_{Water\ in\ Collector}$ The amount of water

	contained in the Collector [kg]
$C_{P,Water}$	Specific heat capacity of water [kJ/(kg · °C)]
$T_{Outlet\ from\ Collector}$	Temperature of water entering the DP [°C]
$T_{Inlet\ to\ Collector}$	Temperature of water leaving the DP [°C]
$T_{Average\ of\ Collector\ in\ evening}$	The average temperature of the collector calculated as the average of $T_{Inlet\ to\ Collector}$ and $T_{Outlet\ from\ Collector}$ [°C]
$T_{Average\ of\ Collector\ in\ morning}$	Same as $T_{Average\ of\ Collector\ in\ evening}$ [°C]
Δt_{Day}	Amount of time with daylight [min]

5.3.2 COMPENSATION FOR ENERGY STORED INSIDE THE DP

To calculate how much energy that was needed to evaporate 1 kg of water from a drying paper ($E_{Evaporate\ 1\ kg\ water}$), first the total energy used to dry one paper ($E_{Dry\ one\ paper}$) was calculated. This was then divided by the weight of the water evaporated from the paper ($m_{Water\ evaporated}$) as seen in Equation 8 below.

$$\boldsymbol{E_{Evaporate\ 1\ kg\ water}} = \frac{\boldsymbol{E_{Dry\ one\ paper}}}{\boldsymbol{m_{Water\ evaporated}}}$$

Equation 8

To calculate how much water that was evaporated from the paper while drying, the paper was weighed before and after drying and the weight difference was used as the weight of the water evaporated (as seen in Equation 9 below).

$$\boldsymbol{m_{Water\ evaporated}} = \boldsymbol{m_{Paper\ before\ drying}} - \boldsymbol{m_{Paper\ after\ drying}}$$

Equation 9

The energy used to dry one paper was then defined as the energy added to the Drier Plate minus the change in stored energy inside the Drier Plate (as seen in Equation 10 below):

$$\boldsymbol{E_{Dry\ one\ paper}} = \boldsymbol{E_{Added\ to\ DP}} - \Delta\boldsymbol{E_{Stored\ in\ DP}}$$

Equation 10

The energy added to the Drier Plate each minute ($\Delta E_{Energy\ added\ to\ DP\ each\ min}$) was then defined as the difference between the average energy in the water flowing into the DP and the average energy in the water flowing out of the DP during each minute (as seen in EQUATION 11 below):

$$\begin{aligned}\Delta \boldsymbol{E}_{\boldsymbol{Energy\ added\ to\ DP\ each\ min}} &= \boldsymbol{E}_{\boldsymbol{Incoming\ to\ DP}} - \boldsymbol{E}_{\boldsymbol{Outgoing\ from\ DP}} \\ &= \dot{\boldsymbol{m}}_{\boldsymbol{Water}} \cdot \boldsymbol{C}_{\boldsymbol{P,Water}} \cdot \left[\boldsymbol{T}_{\boldsymbol{Inlet\ to\ DP}} - \boldsymbol{T}_{\boldsymbol{Outlet\ from\ DP}}\right]\end{aligned}$$

Equation 11

The total energy added to the Drier Plate ($E_{Added\ to\ DP}$) was then obtained by adding together the energy supplied during the whole time that the paper was drying on the DP:

$$\boldsymbol{E}_{\boldsymbol{Added\ to\ DP}} = \Delta \boldsymbol{E}_{\boldsymbol{Energy\ added\ to\ DP\ each\ min}} \cdot \Delta \boldsymbol{t}_{\boldsymbol{Drying\ a\ Paper}}$$

Equation 12

Finally the change in stored energy inside the DP was calculated using the average temperature of the TCs before and after drying a paper. If more energy had been used to dry the paper than was supplied from the Solar Collector, this resulted in a negative value for the change in stored energy in the DP – and naturally, if less energy had been used than supplied it resulted in a positive value (as seen in EQUATION 13 below):

$$\Delta \boldsymbol{E}_{\boldsymbol{Stored\ in\ DP}} = \boldsymbol{m}_{\boldsymbol{Water\ in\ DP}} \cdot \boldsymbol{C}_{\boldsymbol{P,Water}} \cdot \left(\boldsymbol{T}_{\boldsymbol{TCs\ after\ drying}} - \boldsymbol{T}_{\boldsymbol{TCs\ before\ drying}}\right)$$

Equation 13

5.3.2.1 CHAPTER DEFINITIONS:

$E_{Evaporate\ 1\ kg\ water}$	Energy used to evaporate 1 kg of water from a drying paper [MJ]
$E_{Dry\ one\ paper}$	Total energy used to dry one paper [MJ]
$\Delta E_{Energy\ added\ to\ DP\ each\ min}$	Average of the energy added to the DP during the time of drying one paper [MJ]
$E_{Added\ to\ DP}$	Energy added to the Drier Plate during the time of drying one paper [MJ]
$\Delta E_{Stored\ in\ DP}$	Change in stored energy inside the DP [MJ]
$T_{Inlet\ to\ DP}$	Temperature of the water entering the DP [°C]
$T_{Outlet\ from\ DP}$	Temperature of the water leaving the DP [°C]
$m_{Water\ in\ DP}$	Mass of the water inside the DP [kg]
$m_{Water\ evaporated}$	Mass evaporated from the paper being dried [kg]
$m_{Paper\ before\ drying}$	Weight of the wet paper before drying [kg]
$m_{Paper\ after\ drying}$	Weight of the dry paper after drying [kg]
$T_{TCs\ after\ drying}$	Average temperature of the TCs at finishing the drying [°C]

$T_{TCs\ before\ drying}$ Average temperature of the TCs at the beginning of drying [°C]

$\Delta t_{Drying\ a\ Paper}$ Time to dry one paper [s]

5.3.3 USE OF TEMPERATURES TO CALCULATE STORED ENERGY

As the average temperature from the TCs is very close to the average temperature of the water entering and leaving the DP at any single time, the average of the water temperature in and out of the DP could also have been used to calculate the change in stored energy. But as initially the more conservative value was recorded when using the average of the TCs, this is the value that has been used in this report.

5.3.4 LOSS OF ENERGY IN THE SYSTEM

The system losses were not regarded as a very important part of this study as a small study like this one always will have comparably big system losses. But an attempt to estimate these losses was made using EQUATION 14 & EQUATION 15 below:

$$\Delta \boldsymbol{E}_{\boldsymbol{System\ Losses}} = \dot{\boldsymbol{m}}_{\boldsymbol{Water}} \cdot \boldsymbol{C}_{\boldsymbol{P,Water}} \cdot \left(\left[\boldsymbol{T}_{\boldsymbol{Outlet\ from\ SC}} - \boldsymbol{T}_{\boldsymbol{Inlet\ to\ SC}}\right] - \left[\boldsymbol{T}_{\boldsymbol{Inlet\ to\ DP}} - \boldsymbol{T}_{\boldsymbol{Outlet\ from\ DP}}\right] \right)$$

Equation 14

$$\boldsymbol{E}_{\boldsymbol{Daily\ System\ Losses}} = \sum \Delta \boldsymbol{E}_{\boldsymbol{System\ Losses}}$$

Equation 15

5.3.4.1 CHAPTER DEFINITIONS:

$\Delta E_{System\ Losses}$ System losses each minute of a day [MJ]

$E_{Daily\ System\ Losses}$ Total system losses over the whole day [MJ]

5.4 THEORETICAL BACKGROUND: ENERGY ABSORBED BY THE SOLAR COLLECTOR

5.4.1 IRRADIANCE HITTING A HORIZONTAL AND A TILTED SURFACE

To calculate the total irradiance [W/m^2] that is absorbed by a collector lying horizontally positioned flat on the ground, EQUATION 16 is used:

$$\boldsymbol{I_{Total,Horizontal} = I_{Beam,Horizontal} + I_{Diffuse,Horizontal}}$$

Equation 16

For a collector tilted by β° in relation to the ground (used later in EQUATION 21 and EQUATION 22), another component has to be added – the ground reflection. Also the amount of the beam and diffused radiation that hit the collector will be changed so for this situation EQUATION 17 was used:

$$\boldsymbol{I_{Total,Tilted} = I_{Beam,Tilted} + I_{Diffuse,Tilted} + I_{Ground\ reflection,Tilted}}$$

Equation 17

To measure the solar irradiance the two pyrometers mentioned in section 3.4.4.2 Temperature, Humidity and radiation sensors were used as described in section 6.3.1 Measuring the Solar irradiance. This meant that only the total irradiance and the diffuse irradiance hitting a horizontal surface were logged. Thus all other parameters had to be derived from them using the calculations mentioned below – all taken from Duffie and Beckman's book: Solar Engineering of Thermal Processes (Duffie & Beckman, 2006).

5.4.1.1 CHAPTER DEFINITIONS:

$I_{Total,Horizontal}$ Total irradiance hitting a flat surface lying on the ground, corresponding to the pyrometer *without* shading ring [W/m^2]

$I_{Beam,Horizontal}$ The beam irradiance hitting a flat surface lying on the ground [W/m^2]

$I_{Diffuse,Horizontal}$ The diffuse irradiance hitting a flat surface lying on the ground, corresponding to the pyrometer *with* shading ring [W/m^2]

$I_{Total,Tilted}$ Total irradiance hitting a flat surface tilted with regards to the ground [W/m^2]

$I_{Beam,Tilted}$ The beam irradiance hitting a flat surface tilted with regards to the ground [W/m^2]. For more details see section 5.4.2 Calculating the beam component on a tilted surface.

$I_{Diffuse,Tilted}$ The diffuse irradiance hitting a flat surface tilted with regards to the ground [W/m^2]. For more details see section 5.4.3 Calculating the diffuse component on a tilted surface

$I_{Ground\ reflection,Tilted}$ The ground reflection hitting a flat surface tilted with regards to the ground [W/m^2]. For more details see section 5.4.4 Calculating the ground reflection on a tilted surface.5.4.4

5.4.2 CALCULATING THE BEAM COMPONENT ON A TILTED SURFACE

As the beam irradiance (also known as direct irradiance) hitting a horizontal surface was not measured directly, it had to be calculated using EQUATION 18.

$$\boldsymbol{I_{Beam,Horizontal} = I_{Total,Horizontal} - I_{Diffuse,Horizontal}}$$

Equation 18

To then convert this value into the beam irradiance hitting a tilted surface, a conversion factor called R_b was introduced (as seen in EQUATION 19).

$$\boldsymbol{I_{Beam,Tilted} = I_{Beam,Horizontal} * R_b}$$

Equation 19

Where R_b is a geometric factor that with some logical steps can be reduced to EQUATION 20:

$$\boldsymbol{R_b = \frac{\cos\theta}{\cos\theta_z}}$$

Equation 20

Where θ is the angle between the sun and the normal of the tilted plane formed by the surface of the collector (as described in EQUATION 21).

$$\cos\boldsymbol{\theta} = \sin\boldsymbol{\delta}\cdot\sin\boldsymbol{\phi}\cdot\cos\boldsymbol{\beta} - \sin\boldsymbol{\delta}\cdot\cos\boldsymbol{\phi}\cdot\sin\boldsymbol{\beta}\cdot\cos\boldsymbol{\gamma}$$

$$
+\cos\boldsymbol{\delta}\cdot\cos\boldsymbol{\phi}\cdot\cos\boldsymbol{\beta}\cdot\cos\boldsymbol{\omega}
+\cos\boldsymbol{\delta}\cdot\sin\boldsymbol{\phi}\cdot\sin\boldsymbol{\beta}\cdot\cos\boldsymbol{\gamma}\cdot\cos\boldsymbol{\omega}
+\cos\boldsymbol{\delta}\cdot\sin\boldsymbol{\beta}\cdot\sin\boldsymbol{\gamma}\cdot\sin\boldsymbol{\omega})
$$

Equation 21

And $\boldsymbol{\theta_z}$ is the angle between the sun and a horizontal plane (i.e. same as above, but with β = 0), thus EQUATION 21 turns into EQUATION 22:

$$
\cos\boldsymbol{\theta_z} = \sin\boldsymbol{\delta}\cdot\sin\boldsymbol{\phi} + \cos\boldsymbol{\delta}\cdot\cos\boldsymbol{\phi}\cdot\cos\boldsymbol{\omega}
$$

Equation 22

5.4.2.1 CHAPTER DEFINITIONS:

R_b — **Geometric factor**, describing the relation between a horizontal plane and a tilted plane when calculating the portion of the beam irradiance that would hit a tilted surface compared to a horizontal one. $\boldsymbol{R_b}$ is defined as EQUATION 20 when both $\cos\boldsymbol{\theta} > 0$ and $\cos\boldsymbol{\theta_z} > 0$ and as $\boldsymbol{R_b} = 0$ at all other times.

θ — **Angle of incidence**, the angle between the sun and the normal of the collector's surface area [°]

θ_z — **Zenith Angle,** the angle between the sun and the normal of a horizontal surface [°]

δ — **Declination**, the angular position of the sun at solar noon (i.e., when the sun is on the local meridian) with respect to the plane of the equator, north positive: $-23.45° \leq \delta \leq 23.45°$ Calculated for each day as in Duffie & Beckman (2006).

ϕ — **Latitude**, the angular location north or south of the equator, north positive, for Bogra in Bangladesh: ϕ = 24°

β — **Slope**, the angle between the plane of the surface in question and the horizontal, for the collector used: β = 38.5°

γ — **Surface azimuth angle**, the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, as the collector was facing straight south: γ = 0°

ω — **Hour angle**, the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour; morning negative, afternoon positive.

5.4.3 CALCULATING THE DIFFUSE COMPONENT ON A TILTED SURFACE

To then calculate the diffused radiation hitting a tilted surface the Hay and Davies model has been used, as it is a simple model that still has been shown to perform similarly to other, more complex models (Reindl, et al., 1990).

Diffuse radiation can be divided into three parts, isotropic diffuse, circumsolar diffuse and horizon brightening, where the isotropic diffuse part is scattered over the whole sky-dome and can be assumed evenly distributed over the entire sky. Thus for a tilted plane the portion of the plane that will be exposed to this component can be modeled with the help of the view factor seen in EQUATION 23. The circumsolar diffuse part on the other hand is focused mostly in the direction of the sun without being part of the beam radiation and finally the horizon brightening part is concentrated near the horizon.

In the Hay and Davies model the horizon brightening component is included in the isotropic diffuse and the circumsolar diffuse radiation. As mentioned above, to model the part of the isotropic diffuse radiation that hit a tilted plane EQUATION 23 was used to give a value of how big portion of the sky dome that was “visible” to the plane.

$$\boldsymbol{f_{view\ factor,sky}} = \frac{\mathbf{1 + \cos\beta}}{\mathbf{2}}$$

Equation 23

This factor is then multiplied with an estimate of how much of the incoming light that gets diffused (i.e. how cloudy/hazy the weather was) and then a factor was added for the circumsolar part. The final expression for the diffuse radiation in the Hay and Davies model on the tilted surface is thus expressed as in EQUATION 24.

$$\boldsymbol{I_{Diffuse,Tilted}} = \boldsymbol{I_{Diffuse,Horizontal}} \cdot \left[(\mathbf{1} - \boldsymbol{A_i}) \cdot \frac{\mathbf{1 + \cos\beta}}{\mathbf{2}} + \boldsymbol{A_i} \cdot \boldsymbol{R_b} \right]$$

Equation 24

Where A_i is the anisotropy index described in EQUATION 25 and is defined as the ratio between the incident beam radiation ($I_{Beam,Horizontal}$) and the irradiance $I_{Total,No\ atmosphere}$ that would hit a horizontal plane if the earth had no atmosphere.

$$\boldsymbol{A_i} = \frac{\boldsymbol{I_{Beam,Horizontal}}}{\boldsymbol{I_{Total,No\ atmosphere}}}$$

Equation 25

Due to effects such as the distance between the sun and the earth the radiation that hits the earth varies with about 3.3% over the year. Also the angle between the normal of the horizontal plane and the position of the sun on the sky is important so the final expression for $I_{Total,No\ atmosphere}$ turns out to be:

$$I_{Total,No\ atmosphere} = G_{sc} \cdot \left(1 + 0.033 \cdot \cos\frac{360 \cdot n}{365}\right) \cdot \cos\theta_z$$

Equation 26

Where G_{sc} is defined as a fixed constant giving an average value for the irradiance from the sun, hitting the earth before it passes through the atmosphere, and in this paper a value of $G_{sc} = 1367$ W/m^2 has been used. The value *n* corresponds to the amount of days in the year that has passed (i.e. 3 Feb ➔ n = 31+3 = 34).

5.4.3.1 CHAPTER DEFINITIONS:

$f_{view\ factor,sky}$
: The portion of the sky "visible" to a tilted plane [%]

$I_{Total,No\ atmosphere}$
: The irradiance that would hit a horizontal plane on the ground, if the earth had no atmosphere [W/m^2]

G_{sc}
: Extraterrestrial radiation, a fixed constant giving an average value for the irradiance from the sun, hitting the earth before it passes through the atmosphere [W/m^2]: In this paper $G_{sc} = 1367$ W/m^2

n
: The number of days of the year that has passed

5.4.4 CALCULATING THE GROUND REFLECTION ON A TILTED SURFACE

To then calculate the irradiance reflected from the ground a much simpler formula is sufficient (as seen in EQUATION 27). In this model the ground-reflected radiation on the tilted plane is only dependent on the reflectance of the ground and the view factor of the ground, similar to the one mentioned above in EQUATION 23, of the tilted surface. But here the view factor shows how much of the ground (and not the sky) that is "visible" to the tilted plane.

$$I_{Ground\ reflection,Tilted} = I_{Total,Horizontal} \cdot \rho_g \left(\frac{1 - \cos\beta}{2}\right)$$

Equation 27

5.4.4.1 CHAPTER DEFINITIONS:

ρ_g
: The ground reflectance was estimated to $\rho_g = 0.2$, as this is a usual value to use and no better estimation was available.

5.4.5 CALCULATING THE TOTAL ENERGY ABSORBED

After completing the calculations for how big irradiance that hit the collector the next step would be to evaluate how much of this energy [MJ] that actually got absorbed by the collector. But as the optical and absorption properties of the collector were not a big part of this study, an assumption was made that the energy hitting the collector over a full day was following the relations in EQUATION 28 and EQUATION 29.

$$\boldsymbol{E_{Absorbed}} = \boldsymbol{E_{Total,Tilted}} - (\boldsymbol{E_{Optical\ losses}} + \boldsymbol{E_{Absorption\ loss}})$$

Equation 28

$$\boldsymbol{E_{Absorbed}} = \boldsymbol{E_{Converted\ by\ Collector}}$$

Equation 29

Where $E_{Converted\ by\ Collector}$ was defined as in Equation 5. By combining the two equations above into EQUATION 30 the optical and absorption losses could be calculated.

$$(\boldsymbol{E_{Optical\ losses}} + \boldsymbol{E_{Absorption\ loss}}) = \boldsymbol{E_{Total,Tilted}} - \boldsymbol{E_{Converted\ by\ Collector}}$$

Equation 30

Where finally $E_{Total,Tilted}$ was calculated as the total energy hitting the collector over a full day, by adding the average irradiance each hour $I_{Total,Tilted,i}$ with the aperture area ($A_{SC,aperture}$) of the collector as seen in EQUATION 31.

$$\boldsymbol{E_{Total,Tilted}} = \sum_{i=0}^{24} \boldsymbol{I_{Total,Tilted,i}} * \boldsymbol{A_{SC,aperture}} * \Delta \boldsymbol{t}$$

Equation 31

5.4.5.1 CHAPTER DEFINITIONS:

$E_{Absorbed}$	Energy absorbed by the collector during one day [MJ]
$E_{Total,Tilted}$	Energy hitting the collector during one day [MJ]
$E_{Optical\ losses}$	Energy lost due to optical losses during one day [MJ]
$E_{Absorption\ loss}$	Energy lost due to absorption losses during one day [MJ]
$I_{Total,Tilted,i}$	Average irradiance hitting the solar collector each hour [W/m^2]
$A_{SC,aperture}$	Aperture area of the solar collector [m^2]
Δt	Time over which the average irradiance is measured [3600 s]

6 PREPARING FOR THE EXPERIMENTS

After building the drying system and connecting all measurement equipment to a data logger one week of drying tests followed using the Electric Water Heater (EWH) as the heat source. During this time 45 papers were dried but due to power shortages, some data from these tests were not recorded. The last setup used the Solar Collector (SC) as the heat source, and during this phase a total of 56 papers were dried during six days with the Solar Collector as the only heat source. Out of these 56 papers, most were made of cotton and jute as the third type of fiber, straw, was only available in the very end, and thus only a few papers with that fiber type were used.

6.1 CATEGORIZATION OF THE PAPERS

After completing the setup, tightened all water leaks, made sure that the Drier Plate could be heated efficiently, and that the data logger recorded all data as planned – the next step was to prepare the actual drying tests. As the testing of the new system took place at the center for development of sustainable technology outside of Bogra, and not at one of the paper producing centers, papers that already had been dried once had to be soaked in water and then dried again. To still have a good material to work with, papers of several different fiber types and thicknesses were sent to the development center, but initially only papers of cotton and jute were brought to Bogra.

6.1.1 WEIGHING AND LABELING THE PAPERS

The first step in preparing for the experimentation was therefore to establish the dry weight of all papers, label them and decide what test to do first. To structure the experimentations all papers were therefore marked with a serial number (1, 2, 3, … 12), where each fiber type also had a separate list starting from 1 with the first letter of the fiber type preceding the number. The cotton paper with serial number 3 was therefore called C3 and the Jute paper with serial number 9 was called J9 (see Table 2 for full lists). To establish the dry weight all papers were weighed and the weight was noted as the weight during storage conditions, as they had been stored for many days and could therefore be considered in balance with the humidity under storage conditions.

6.1.2 LIST OF WEIGHT FOR DRY AND WET PAPERS USED IN THE EXPERIMENTS

As can be seen in Table 2 the average dry weight of a cotton paper was 0.137 kg while the average wet weight for the same papers was 0.385 kg. The same data can be found for jute papers: 0.133 kg (dry weight) and 0.545 kg (wet weight) and for straw papers: 0.188 kg (dry weight) and 0.477 kg (wet weight). It is therefore clear that both the jute papers and the straw papers could hold more water per kg dry paper, compared to the cotton papers. In TABLE 3 the size of the biggest and the smallest papers are given in cm. For an even more extensive list, see Appendix F: Weight of papers – Full list.

TABLE 2 LIST OF DRY WEIGHT AND AVERAGE WET WEIGHT FOR COTTON, JUTE AND STRAW PAPERS DRIED WITH BOTH THE ELECTRIC WATER HEATER AND THE SOLAR COLLECTOR.

Paper #	Dry weight (kg)	Wet weight (kg)
CX	0.110	0.363
C1	0.120	0.367
C2	0.135	0.388
C3	0.115	0.334
C4	0.150	0.418
C5	0.145	0.430
C6	0.130	0.395
C7	0.135	0.350
C8	0.160	0.447
C9	0.140	0.396
C10	0.155	Not recorded
C11	0.150	Not recorded
C12	0.140	0.345
Average Cotton	0.137	0.385
J1	0.120	0.529
J2	0.130	0.559
J3	0.135	0.573
J4	0.155	0.652
J5	Not recorded	Not recorded
J6	0.130	0.539
J7	0.135	0.555
J8	0.135	0.531
J9	0.155	Not recorded
J10	0.145	Not recorded
J11	0.105	0.420
J12	0.115	Not recorded
Average Jute	0.133	0.545
S1	0.120	0.495
S2	0.120	0.498
S3	0.115	0.456
S4	0.115	0.458
Average Straw	0.118	0.477

TABLE 3 SIZE OF ALL PAPERS DRIED WITH BOTH THE ELECTRIC WATER HEATER (EWH) AND THE SOLAR COLLECTOR (SC).

Size (cm)	
All papers were smaller than:	60x90
All papers were bigger than:	55x80

The paper J5 had been used and re-used several times in drying tests during the initial setup phase, before all papers were categorized, and had then been handled so badly that it broke. Therefore no exact weight was recorded for that paper. Also the papers C10, C11 J9, J10 and J12 were never dried in a recorded test, as it was judged more interesting to dry a smaller amount of papers at different temperatures rather than drying all papers. The paper marked as CX was an unmarked thick cotton paper that was used for the first four drying tests. In the notes from the experiments it was only noted that the same cotton paper was used for all four tests, that the paper initially weighed 110 g – but no serial number. As no other cotton paper has a storage weight of 110 g, this most likely was one of the older papers lying around in the workshop from before. Papers made from straw also became available in the end of the experimentations, but at that point not much time remained before M. Hjort had to return to Sweden. Therefore these papers were only dried about 2-3 times each, but that was enough to gather the data required to include some results for straw-papers as well in the report - even if the conclusions for these papers are a little less certain than the ones for jute and cotton.

6.1.3 SOAKING THE PAPER WITH WATER

To minimize the variations in how much water the papers absorbed during the soaking process a standard was developed for how to do this. The paper was first soaked with water by dipping it in a water bucket, but the bucket was too small to fit the entire paper, instead the paper was rolled to a tube and soaked one half at the time. To even out the water content in the paper; the final step was to pour more water on the paper after laying the paper flat on a metal sheet. Finally the metal sheet was positioned at an angle to remove excess water with the help of gravity. The wet paper was then weighed and put on the Drier Plate to get dried.

6.2 DEVELOPMENT OF THE DRYING TESTS

6.2.1 MEASURING THE SURFACE TEMPERATURE OF THE DRIER PLATE FRONT SIDE VS. BACKSIDE

As mentioned in section 4.4 Measuring the temperature of the system a set of nine TCs was used to measure the surface temperature of the Drier Plate. In the initial tests these TCs were placed on the front side of the DP, between the paper and the steel sheet. This setup resulted in a very interesting effect in that the temperature dropped with every new paper that was put on the Drier Plate as can be seen in Figure 29 below.

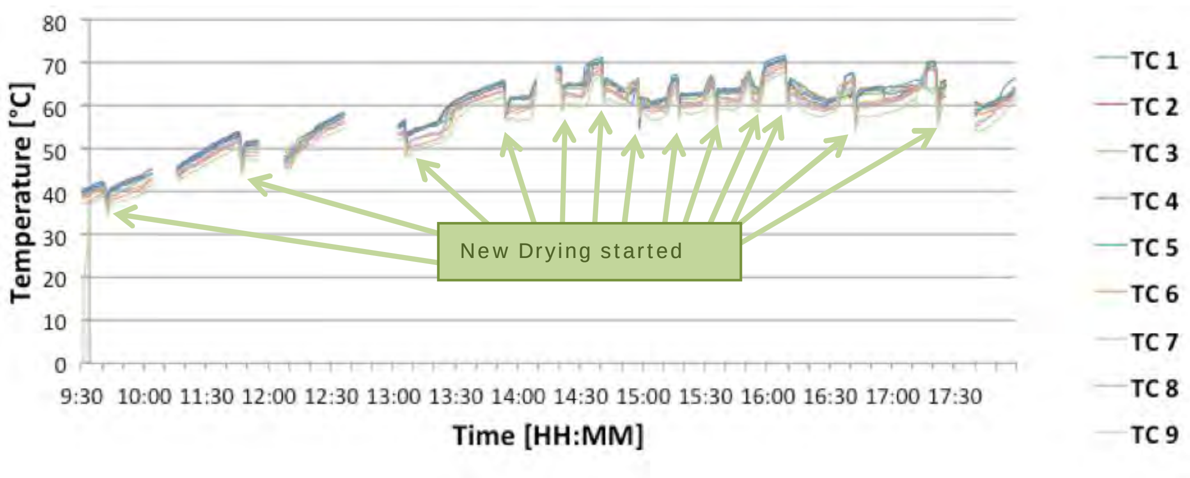

FIGURE 29 VARIATION IN TEMPERATURE ON THE FRONT SIDE OF THE DRIER PLATE, AS SHOWN BY THE NINE THERMO COUPPLES (TCS) DURING THE FIRST DAY OF DRYING PAPERS.

The temperature at all nine TCs drops 2-8°C in less than 2 min after a paper has been put on the Drier Plate. On the other hand, in just as short a time, the temperature goes back up again to a new "steady state" temperature that continues as long as the paper is "boiling off" the excess water inside. This effect can be seen even better when zooming in on just one test. In Figure 30 below it is clear that the temperature drops at all nine positions and that the temperature then is quite stable during the phase when excess water is being "boiled off".

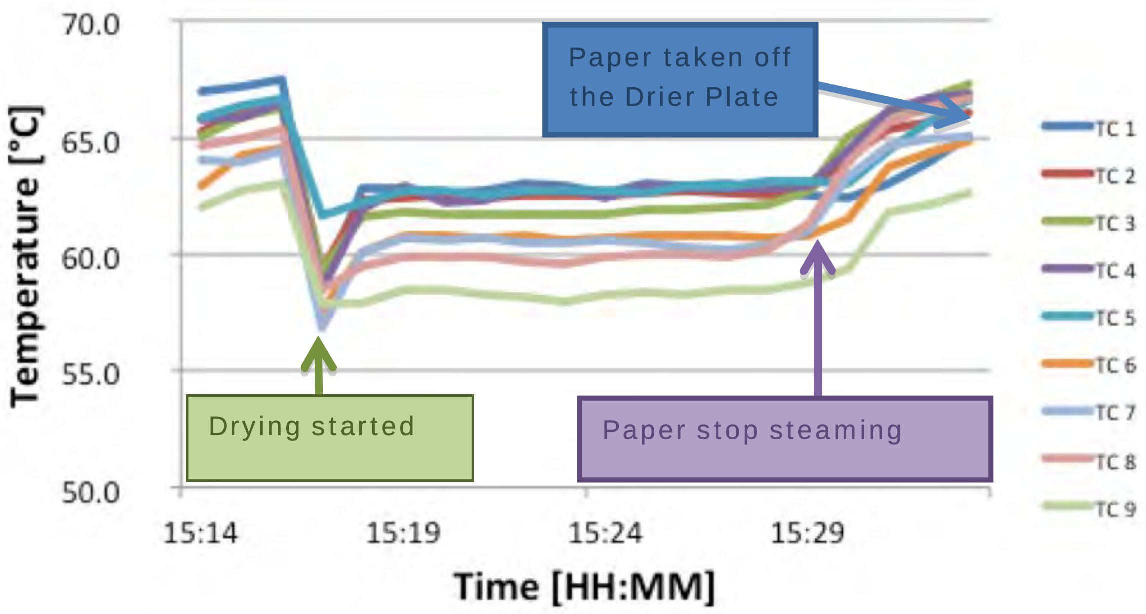

FIGURE 30 DRYING EWH8 ON THE 19TH JAN 2011 – A CLEAR DROP IN TEMPERATURE IN THE BEGINNING AND THEN A FLAT TEMPERATURE UNTIL THE PAPER STOPS STEAMING IN THE END.

The shape of the curves in Figure 30 corresponds well with the theory of how papers dry. At first the paper is cold and wet and therefore cools down the TCs as it absorbs heat from the Drier Plate, which results in a drop in the temperature. As the paper heats up and water starts to turn into steam also the area between the paper and the DP heats up. But as the water never gets hotter than the boiling temperature before it turns into steam and leaves the paper, this phase corresponds to a very constant temperature in the paper. When the water film between the paper and the surface of the DP dries up and the thermal properties of the paper start to change due to the lower water content, this results in a lower heat transfer to the paper. Consequently the heat in the region between the paper and the DP starts to build up again. To confirm this correlation three different times were noted down, i.e. the time when the

1. paper was put on the DP
2. paper stopped steaming visibly
3. paper was dry and therefore taken off the DP

It is then clear that these times also correspond well with the change in the temperature between the paper and the front surface of the Drier. As interesting data could be gathered from both placing the TCs on the front side and the backside of the Drier Plate, a decision had to be made of which setup to use. To compare the two setups five of the TCs were placed on the back of the DP and the average temperature of the four TCs on the front versus the average of the five on the back can be seen in Figure 31 below. It was then clear that the rapid change in the temperature that was recorded from the TCs on the front was not followed by the TCs on the back. Instead the temperature changes recorded from the TCs on the back correlate well with the temperature variation of the water inside the drier (as was shown already in section 4.5.2 Using the TCs to determine the temperature inside the DP).

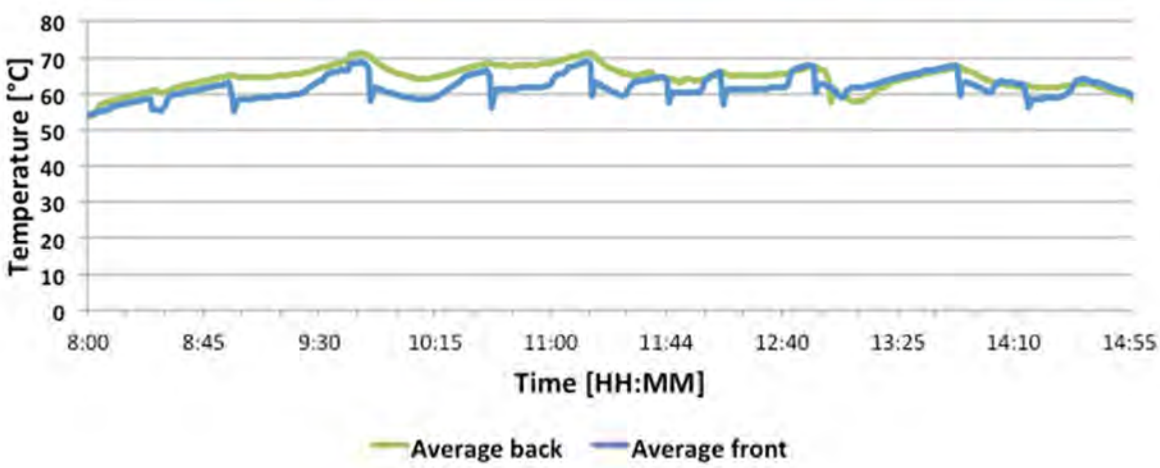

FIGURE 31 DIFFERENCE IN TEMPERATURE VARIATION RECORDED BY TCS PLACED ON THE BACK VS. THE FRONT OF THE DRIER PLATE. RECORDED ON THE 20TH JAN 2011.

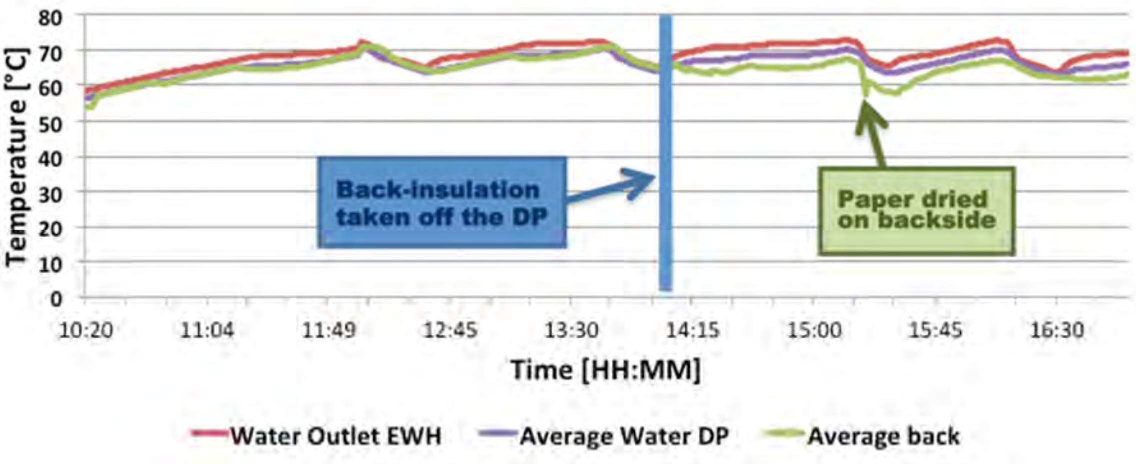

FIGURE 32 CORRELATIONS BETWEEN THE TEMPERATURE VARIATION OF THE WATER LEAVING THE EWH, THE WATER INSIDE THE DP AND THE BACK SURFACE TEMPERATURE OF THE DP. RECORDED ON THE 20TH JAN 2011.

On the other hand it is clear from Figure 32 that this correlation decreases if no insulation layer is protecting the TCs from the ambient temperature. After the back-insulation (seen in Figure 33) was removed there is a clear difference between the average water temperature inside the Drier and the average temperature recorded by the thermocouples. Figure 32 also show an extra big drop in the temperature recorded by the back TCs at 15:20 when a paper was dried on the backside as well as on the front side. This was the only time when papers was dried on both sides at the same time, as it was regarded as hard to compare this data with the other tests were only one paper had been dried. Also, as mentioned in chapter 4.2 Building the Drier Plate, the backside of the DP was far from optimal for drying papers. By only drying one paper at the time it was also easier to calculate how much energy that had been used to evaporate a certain amount of water from the paper being dried.

FIGURE 33 BACK-INSULATION ON THE DRIER PLATE THAT INSULATES THE TCS FROM THE AMBIENT TEMPERATURE.

The conclusions in the end was therefore that even if it was interesting to see how the temperature changed between the paper and the DP while the papers were being dried – there was too many drawbacks with this setup. Some other reasons were also that the TC's underneath the paper resulted in less efficient drying of the paper above the TC; as a result these areas were damp longer than the surrounding parts of the paper. Another problem was that some thermocouples got ripped off when a paper was removed which resulted in a lot of extra work refitting the TCs on the Drier Plate. So finally all TCs was moved to the back of the DP and where then used only for calculating the change in stored energy inside the Drier Plate.

6.3 INCLUDING THE SOLAR COLLECTOR

The goal of the project was to evaluate the use of an evacuated water-in-glass H-type collector with a gross area of 7.3 m^2 and an aperture area of 5.0 m^2 (seen in Figure 34 below). As soon as the Solar Collector arrived to Bogra and had been assembled, it was included in the loop instead of the EWH. At this point the UPS was set to give back-up electricity to both the Data logger and the Pump, thus making the tests practically independent on whether there was a power black-out or not.

FIGURE 34 H-TYPE WATER-IN-GLASS COLLECTOR USED IN THIS THESIS

6.3.1 MEASURING THE SOLAR IRRADIANCE

When using the solar collector as the heat source it was also important to measure and log the solar radiation hitting the collector. To do this two pyrometers were used, one was measuring the total irradiance hitting a horizontal surface in parallel with the ground while the other one had a shading-ring (as seen in Figure 35) to block out the direct sunlight, and thereby only record the diffuse radiation.

FIGURE 35 TWO PYROMETERS MOUNTED ON A METALROD ABOUT 60 CM AWAY FROM EACH OTHER, ONE WITH A SHADING-RING TO BLOCK OUT DIRECT SUNLIGHT.

This ring had to be moved manually a few times, partly to compensate for the difference in the path (across the sky) that the sun takes from one day to the next – but perhaps also due to a mistake in the mounting angle of the ring. Another way to fix this would be to use a wider ring, but then it would also block more of the diffuse light.

The data recorded was then used to calculate how much energy that hit the collector during the same day. As the collector was mounted with an angle of 38.5° in relation to the ground and facing straight southwards (seen in Figure 36) instead of lying flat on the ground – this angle had to be taken into account when estimating the energy hitting the collector. It was also important to define which area that would be used. In this project the aperture area of the collector (5.0 m^2) has been used as it was regarded as the area that would be easiest to compare with another collector, if one would be used in future tests. But also the gross area (7.3 m^2) or the absorber area (4.0 m^2) could have been used. The aperture area was calculated by multiplying the length of a tube exposed to the sun, with the width of the outer tube and the number of tubes, while the absorber area used the width of the inner tube. The gross area on the other hand is important as it gives an indication of how big space that will be needed to fit the collector. But as it would have included the empty spaces between the tubes, it would have overestimated the amount of energy that the collector actually was exposed to.

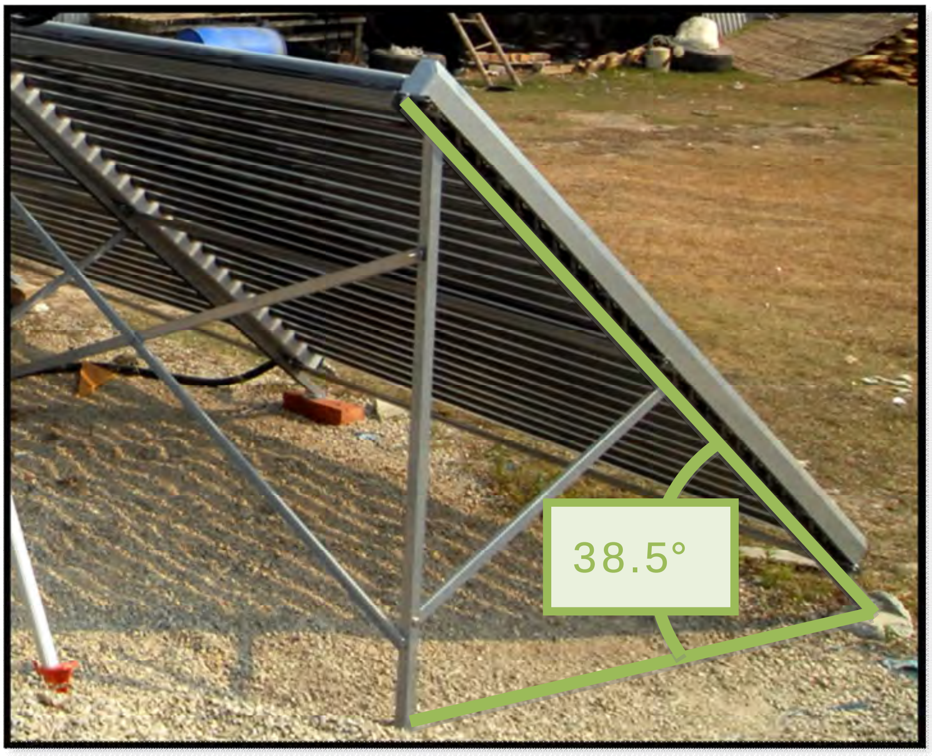

FIGURE 36 THE SOLAR COLLECTOR SEEN FROM THE SIDE. THE ANGLE BETWEEN THE GROUND AND THE COLLECTOR WAS 38.5°

Also the area of the tube facing the sun was constant as the tube-shape results in the same area always facing the sun, no matter how high or low the sun was on the sky. Thus the collector was passively "tracking" the sun in one dimension. This means that the losses due to the sunrays hitting the collector with an angle only depended on the difference in the sun's position in an east west direction. But as these tests did not have the intent to give more than a rough picture of the efficiency of the collector, this effect has been overseen. Instead the equations derived in section 5.4 Theoretical background: Energy absorbed by the solar collector has been used.

7 RESULTS FROM THE SOLAR COLLECTOR AND ANALYSIS

After setting up the system it was finally time to start dry papers. This part of the experimentations was naturally divided into two phases.

- *Phase 1: drying with the electric water heater (EWH)*
- *Phase 2: drying with the solar collector (SC).*

After compensating for the change in stored energy inside the drier plate (DP) during each drying-test it has been possible to compare all the measurements done in both phases directly with each other, and it is clear that they show the same trends.

The main results from the tests with the solar collector were:

(1) *The SWERA data for Bogra held up as a good estimate for the solar input (predicting a yearly average of 17.17 MJ/m^2 and day)*
(2) *The collector could absorb on average 71% of the irradiance that hits the collector over a full day.*
(3) *The SC can provide an average drying power of 25.8 MJ per day (yearly average).*

Finally, the main results from the tests regarding drying of papers were:

(4) *The energy required to dry a paper was not dependent on the fiber type, the water content or the temperature of the drier plate; this value was instead only dependent on the efficiency of the system (as mentioned below). The drying time on the other hand was strongly linked to both the temperature of the DP and the water content of the paper before drying.*
(5) *An average energy of 4.8 MJ was needed to evaporate 1 kg of water from the drying papers when including the system losses (to be compared with the old system that used 8 MJ per kg water evaporated).*
(6) *When focusing on the energy extracted from the drier plate (disregarding system losses as they are dependent on the current setup), as little as 3.5 MJ was needed for the same task (to be compared with the theoretical minimum of 2.6 MJ per kg water evaporated[o]).*
(7) *With the assumption that an average paper holds between 0.248 kg (cotton) and 0.412 kg (jute), one collector (as the one used in this test) can dry between 6 530 and 10 850 papers each year.*

[o] The theoretical minimum energy needed to evaporate 1 kg of water from 10°C to steam.

7.1 NUMBER OF PAPERS DRIED EACH DAY

Finally everything had been set up; the solar collector (SC) was generating hot water, papers were dried and data recorded (as can be seen in Figure 37). So at last the most important tests could be conducted – to test how well a solar collector can dry hand-made papers in Bangladesh.

FIGURE 37 COTTON PAPER BEING FASTENED TO THE DRIER PLATE.

Because the cotton paper took shorter time to dry, more of the initial tests were conducted with papers made from cotton, while more papers dried in the end were made from jute and straw (as seen in Figure 38). The reason for this was initially to gather data from so many drying events as possible in the short time frame given. Once a substantial amount of papers had been dried, less cotton papers were dried in order to also gather data for the other types of papers at the full range of temperatures used to dry the cotton papers.

This relation is even clearer in Figure 39, were it is easy to see that 60% of the papers dried with the first setup (i.e. dried with the electric water heater) were made of cotton, while only 40% of the papers dried with the SC were made of cotton. In total this resulted in about 50% of all papers dried being made from cotton, about 40% jute and only 10% of the papers were made of straw.

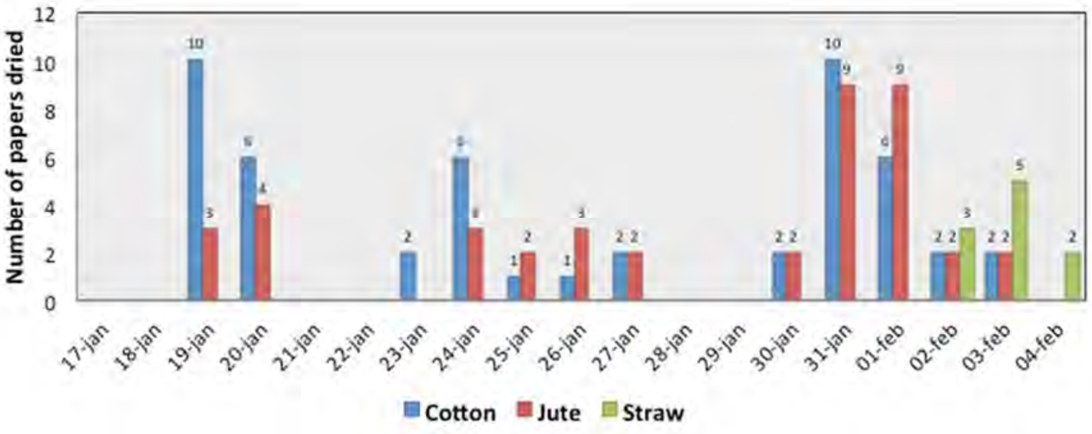

FIGURE 38 AMOUNT OF PAPERS DRIED EACH DAY, DIVIDED INTO THE THREE FIBER TYPES, COTTON, JUTE AND STRAW.

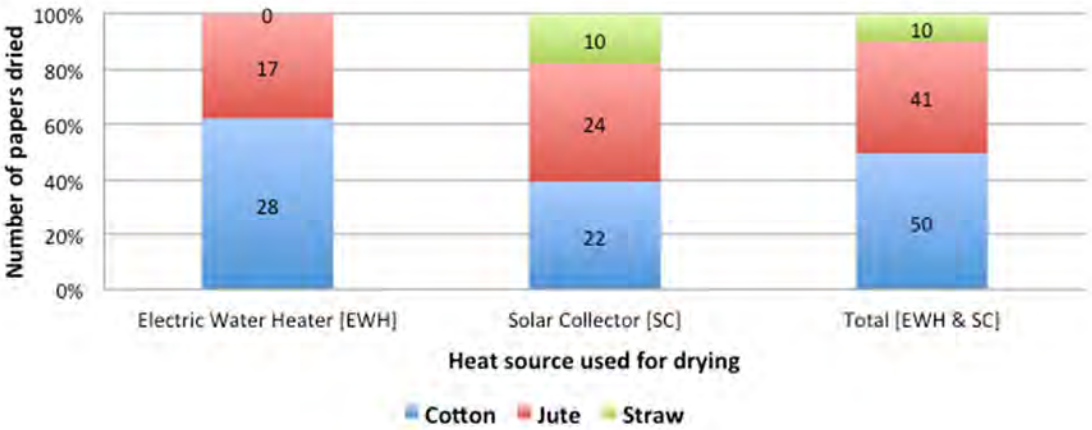

FIGURE 39 THE AMOUNT OF PAPERS DRIED DIVIDED PER TYPE AND HEAT SOURCE USED FOR DRYING.

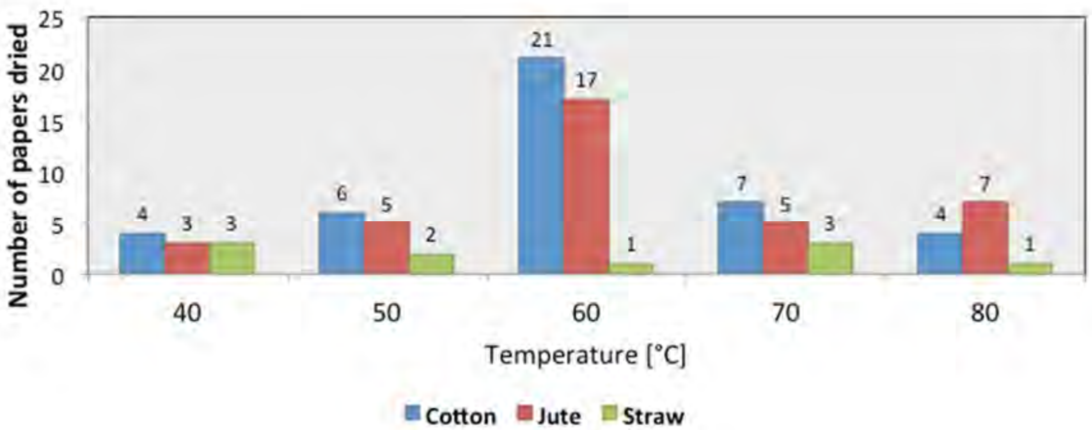

FIGURE 40 THE AMOUNT OF PAPERS FROM EACH FIBER TYPE THAT WAS DRIED IN DIFFERENT TEMPERATURE INTERVALS.

Looking instead on the temperature distribution, it is clear that most papers were dried in the temperature interval of 60° to 70° C (as can be seen in Figure 40), thus the data that are most reliable are in the same temperature interval. The reason that most papers where dried in this interval is that 60°-70°C was a good temperature for drying, as lower temperatures meant that it took longer time to dry the papers, and for higher temperatures a big part of the day was spent just waiting for the drier to heat up.

This problem became easier to handle when the solar collector was used as heat source because the SC could supply more hot water than the EWH (calculated over a full day). That meant that the drier could be used during the morning to dry papers at lower temperatures, and still reach so high temperatures in the afternoon that a bypass loop (made of a long water tube rolled up in a bucket of cold water) had to be connected as a heat sink between the DP and the flow meter to protect it from too high water temperatures.

7.2 DRYING TIME

7.2.1 DEPENDENCY ON FIBER TYPE AND TEMPERATURE

As seen in Figure 39, about 45 papers were dried using the EWH as heat source. Out of these 45 data sets, only a total of 36 papers (14 made of jute and 22 made of cotton) were dried successfully while the remaining 9 sets of data contained lost data points due to power cuts or other disturbances. Already from these data, some important conclusions could be made such as the exponential decline in drying time as the temperature rises, and it was also clear that it took longer time to dry a paper made from jute compared to a paper made from cotton (as seen in Figure 41).

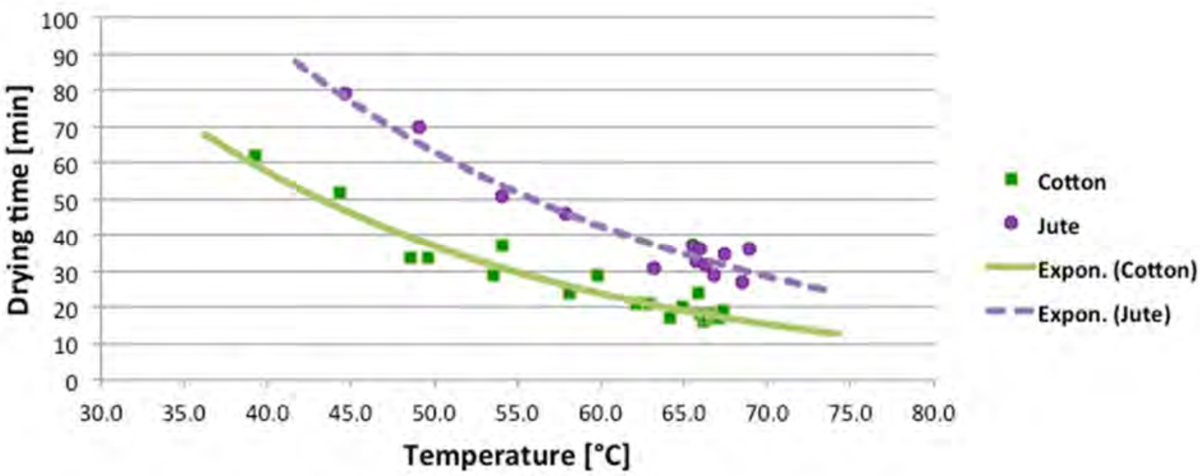

FIGURE 41 DRYING TIME IN MINUTES FOR A PAPER MADE OF EITHER JUTE OR COTTON, DEPENDING ON THE TEMPERATURE OF THE DP. BASED ON DATA RECORDED WHILE THE ELECTRIC WATER HEATER WAS USED AS HEAT SOURCE.

7.2.2 DEPENDENCY ON WATER CONTENT AND TEMPERATURE

When comparing the weight of the papers before and after drying, it was clear that a paper made of jute had lost more water during the drying process compared to the cotton papers. It was natural to recalculate the data to compensate for this effect, thus extrapolate the time it would take to evaporate 1 kg of water from the papers.

After this compensation it was clear that a paper made of jute and a paper made of cotton now followed two very close curves. This is shown in Figure 42 below, and these points very strongly towards the conclusion that it takes the same time to evaporate 1 kg of water from a paper, independent of fiber type. But the fiber type is still an important aspect, as the amount of water that the paper contains is closely linked to the fiber type.

This prediction also held when including the data from the tests using the solar collector as the heat source (as seen in Figure 43 below). Here data from 89 papers were included (42 made of Cotton, 37 made of Jute and 10 made of straw), and it is clear that the time to evaporate 1 kg of water from a paper, more or less followed the same curve regardless of fiber type.

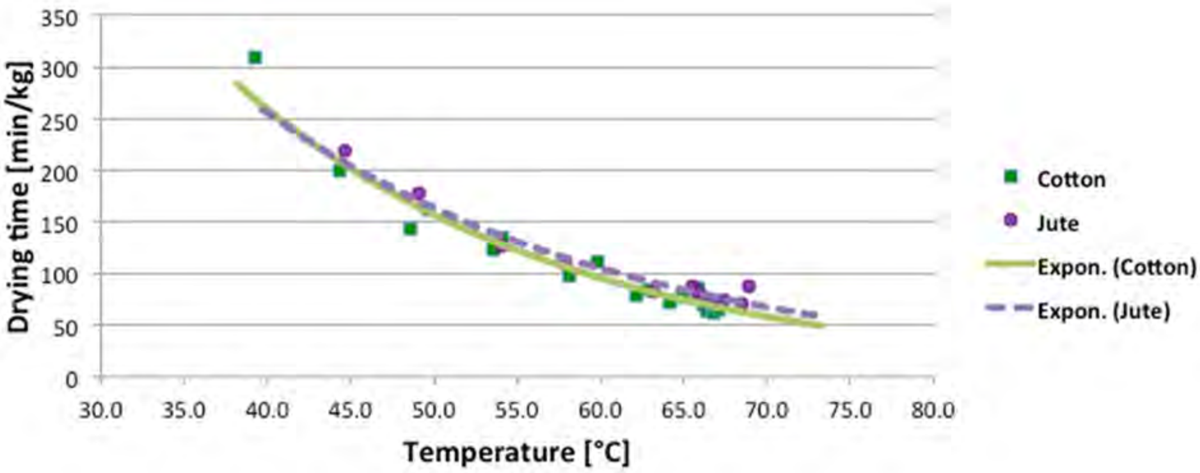

FIGURE 42 TIME TO EVAPORATE 1 KG OF WATER DEPENDING ON FIBER TYPE (MIN/KG), DEPENDING ON THE TEMPERATURE OF THE DP. BASED ON DATA RECORDED WHILE THE ELECTRIC WATER HEATER WAS USED AS HEAT SOURCE.

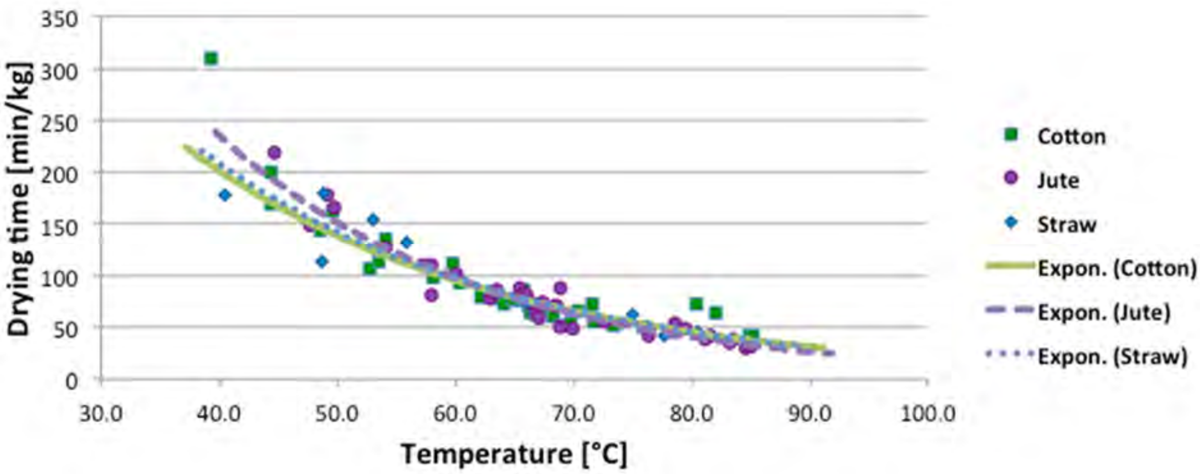

FIGURE 43 TIME TO EVAPORATE 1 KG OF WATER DEPENDING ON FIBER TYPE (MIN/KG), DEPENDING ON THE TEMPERATURE OF THE DP. BASED ON ALL SUCCESSFUL DRYING TESTS RECORDED.

In the end it actually took a few minutes less time to evaporate one kg of water from a paper made of jute then a paper made of cotton at really high temperatures, such as an average water-temperature of 85°C inside the DP. This contrasts to the situation at lower temperatures where the cotton papers always dried faster. But the variation is very small and can be a result of the low resolution on the time measurements (where an error of +/- 60 seconds is possible) as the total time for drying a paper could be as low as 10 minutes for cotton papers and 15 minutes for jute papers (before recalculating to min/kg).

7.3 ENERGY REQUIRED TO DRY A PAPER

7.3.1 ENERGY EFFICIENCY OF THE DRIER PLATE

Looking at how much energy that was needed to evaporate 1 kg of water from the papers using the new DP, it was clear that the energy needed was more or less constant, independent of the temperature of the DP (as is seen in Figure 44 below). For cotton the average energy needed to be added to the DP, to evaporate 1 kg of water from the paper was about 3.54 MJ and for jute the same figure was 3.42 MJ. The straw papers needed on average 3.67 MJ to evaporate 1 kg of water. But as only 10 papers made from straw were dried, the reliability of the data is not as good as the data for the jute and cotton papers. The average energy needed to evaporate 1 kg of water from a paper regardless of fiber type was thus 3.5 MJ.

This is a very good result, just 0.9 MJ more than the 2.6 MJ/kg limit, that is the theoretical minimum energy that always will be needed to evaporate one kg of water at atmospheric pressure. The additional energy required here is due to the imperfect insulation of the DP on surfaces not used for drying, as well as the fact that some extra energy is needed to free the water molecules from the fibers within the paper, and then to transport the water to the surface of the paper. But the data in Figure 44 only cover the energy extracted from the hot water passing the drier plate.

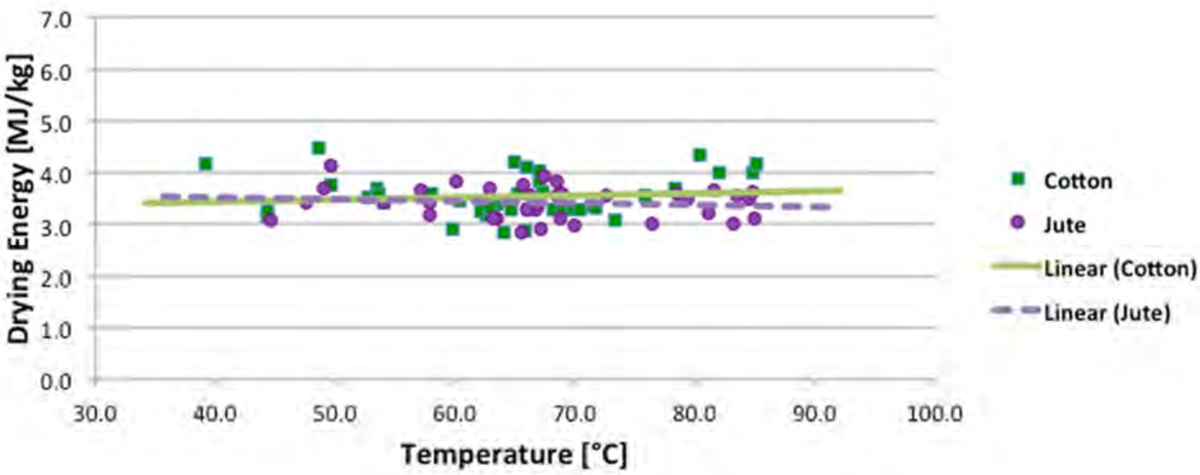

FIGURE 44 ENERGY (EXCLUDING SYSTEM LOSSES) USED TO EVAPORATE 1 KG OF WATER (MEASURED IN MJ/KG OF WATER) FROM THE PAPERS DEPENDING ON FIBER TYPE AND TEMPERATURE USING DATA WHERE BOTH THE EWH & THE SC WERE USED AS THE HEAT SOURCE.

7.3.2 ENERGY EFFICIENCY OF THE DRIER PLATE + SYSTEM LOSSES

To be able to compare the efficiency of the new system with the old one, the energy losses from the whole system also need to be included. Figure 45 shows the energy extracted from the collector at the same time as the papers shown in Figure 44 were dried. It is clear that the graphs in both figures follow the same pattern, except that the average energy required to evaporate 1 kg of water from a paper was increased from 3.5 MJ to 4.8 MJ.

This value is more reasonable to compare with the 8 MJ/kg of water evaporated (that is estimated to be the energy use of the old system) as the estimated energy use in the old system was calculated based on the amount of energy released from the burning wood. The extra 1.3 MJ extracted from the SC and EWH that were not used to dry the papers – were lost to the surrounding air when the water passed through tubes and other equipment that were circulating the water. With better insulation around these tubes, it should be possible to reduce the system losses even more in a permanent setup.

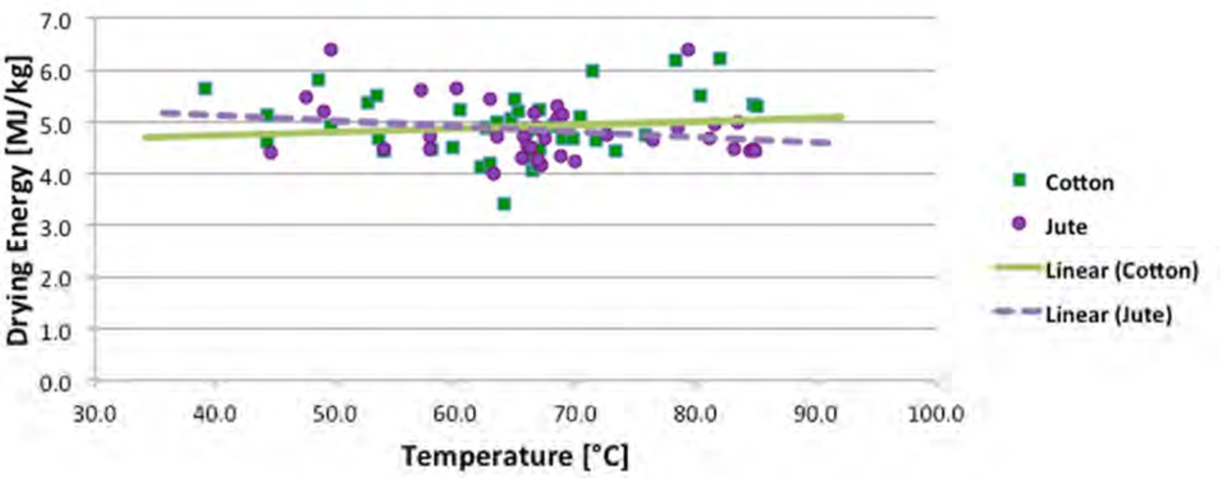

FIGURE 45 ENERGY (INCLUDING SYSTEM LOSSES) USED TO EVAPORATE 1 KG OF WATER (MEASURED IN MJ/KG OF WATER) FROM THE PAPERS DEPENDING ON FIBER TYPE AND TEMPERATURE. USING DATA WHERE BOTH THE EWH & THE SC WERE USED AS THE HEAT SOURCE.

7.3.3 CONVERSION EFFICIENCY OF THE COLLECTOR

The next step was then to calculate how much energy that had hit the collector during the drying period. Due to the big lag from the point that the sun's energy started heating the collector, until a paper was dried using this energy, only daily averages were calculated. To do this, the data from the pyrometers have been recalculated as described in section 5.4 Theoretical background:
Energy absorbed by the solar collector to give the total energy hitting a collector tilted 38.5° in relation to the ground, and facing straight southwards. In Figure 46 below this figure is given per square meter for each of the five days that the solar collector was used as the heat source, and next to that the energy that would have hit a collector mounted parallel (per square meter), and finally the average energy

(calculated per month for January and February separately) hitting a collector mounted parallel to the ground (per square meter).

It is here clear that the energy varied quite a lot from one day to the other, with the period-minimum on the 31st of January (12.5 MJ/m^2) and the maximum on the very next day (19.6 MJ/m^2). It is also clear that due to the low angle of the sun (in the winter) the tilted surface was exposed to more energy than a surface parallel to the ground, thus the average of 16.8 MJ/m2 given in the SWERA data for February would be even higher if recalculated to compensate for this fact. And as the collector is passively tracking the sun in one dimension (due to the rounded shape of the surface of the absorber tubes), an expectation can be made that the solar input at any time during the year will not be lower than the value given by the SWERA data for a flat surface lying on the ground. Using this approach, the yearly energy input given by the SWERA data is 17.17 MJ/m^2 and day, and has therefore been considered a good value to use to extrapolate the expected energy input provided to the collector over a full year.

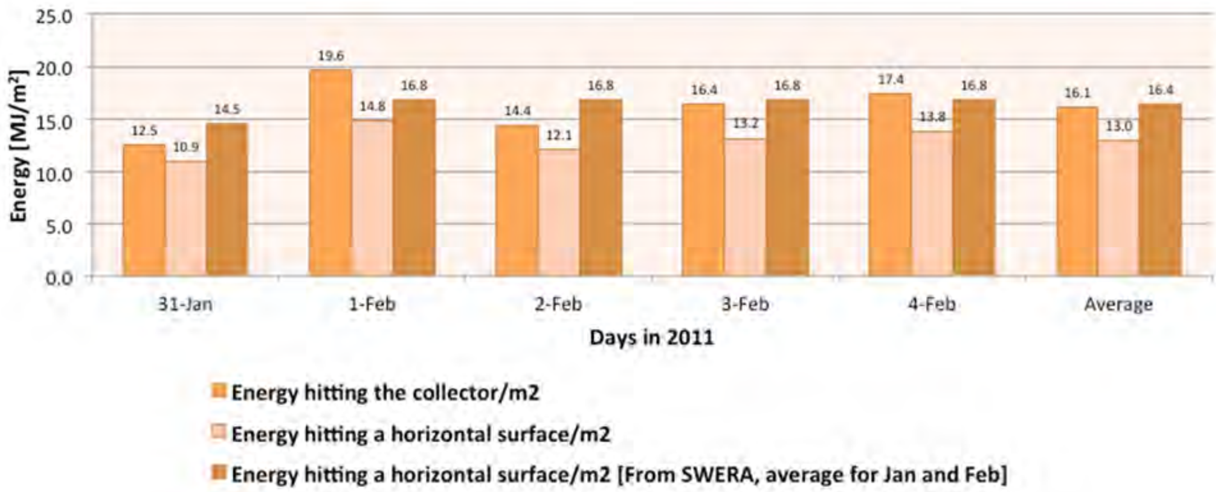

FIGURE 46 COMPARISONS BETWEEN THE ENERGY HITTING THE COLLECTOR/M^2, THE ENERGY RECORDED BY THE UNSHADED PYROMETERS/M^2 DURING THE 5 DAYS, AND FINALY THE AVERAGE ENERGY HITTING A HORIZONTAL SURFACE EACH MONTH ACCORDING TO THE SWERA DATA.

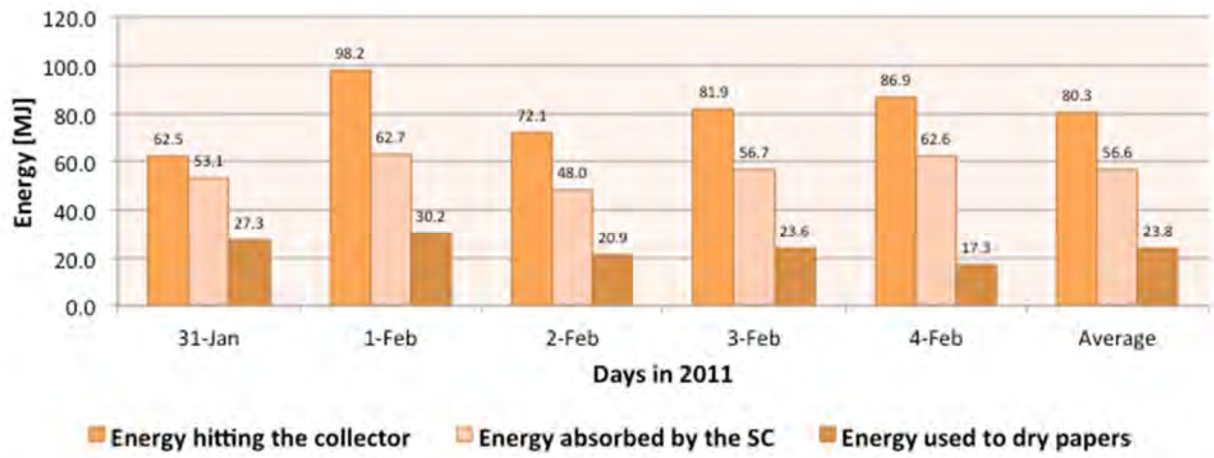

FIGURE 47 COMPARISONS BETWEEN THE ENERGY HITTING THE COLLECTOR, THE ENERGY EXTRACTED FROM THE COLLECTOR AND THE ENERGY USED TO DRY PAPERS DURING 5 DAYS

But to get a sense of how much of this incoming energy that can be used to perform some useful work, the energy intake had to be compared to the energy extracted from the collector, and then also with the energy used to dry papers over a full day. Figure 47 above shows the total energy hitting the tilted solar collector (5 m^2 aperture area), the total energy that was extracted from the collector plus the change in stored energy inside the collector during each day, and finally the energy lost over the drier plate plus the change in stored energy inside the DP during each day.

Because many changes were made to the setup during the 5 days when the solar collector was used as the heat source, it has not been possible to only use the date of uninterrupted drying. Therefore the data recorded also include time periods when changes were made to the set up and no paper was dried. This resulted in a lower efficiency of the system and thus a higher efficiency can be expected at normal operations. The solar collector did also heat up so much some days that a heat sink had to be introduced after the Drier Plate to lower the temperature of the water on the cold side, in order to not overheat the flow meter. This of course also decreased the efficiency and this effect was extra notable on days like the 4th of February when the bypass heat sink was turned on from 09:10 in the morning until the end of the day.

This can then be compared with days like the 31st of January, when the system was used to dry papers from 10:00 to 20:40. It is clear from Figure 47 that the energy lost from the DP to the surrounding was just 17.3 MJ on the 4th of February even if the input was 86.9 MJ, while the energy used to dry papers on the 31st of January was as high as 27.3 MJ even if the intake was only 62.5 MJ.

To make it easier to compare the relative efficiency of each day these data have been recalculated to show the energy levels in relation to the incoming energy of that day, and these data are shown in Figure 48 below.

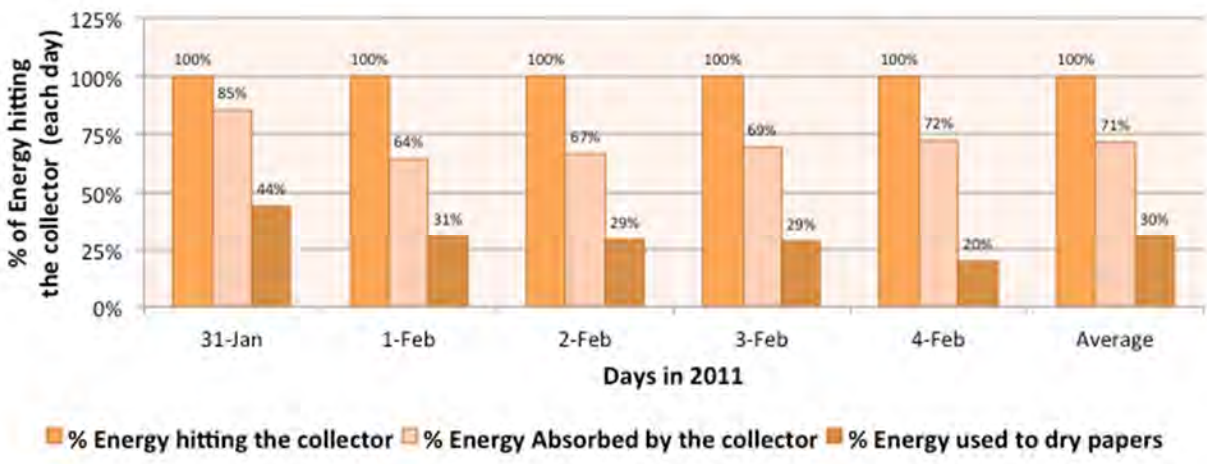

FIGURE 48 PERCENTAGE OF THE ENERGY HITTING THE COLLECTOR THAT IS CONVERTED INTO USEFUL ENERGY.

From Figure 48 it is clear that between 64% and 85% of the energy hitting the collector could be converted into heat inside the collector (with an average conversion efficiency of 71%). This is in line with the expected energy conversion for this type of system. When combining the information in Figure 47 with the one in Figure 48, it is clear that the collector was the most efficient on the same day that the most papers were dried, even if that also was the day with the least solar radiation (31st of January). It does also clearly show that the conversion efficiency of the following three days was almost exactly the same even if the solar input varied a lot from one day to another. But even with the complications mentioned earlier in this chapter, where the low utilization of the system was expected to lower the overall efficiency, as much as 30% of the energy hitting the collector could be used to dry papers. The rest of the absorbed energy was lost due to system losses during operation, and during idle times when the DP was not being used, such as in the evenings. Thus the conclusion was drawn that at least 30% of the incoming energy will be possible to use to dry papers.

To conclude this section: with an incoming energy of 17.17 MJ/m^2 and day, and a collector with an aperture area of 5 m^2, and an efficiency of at least 30%, that is a minimum drying power of 25.8 MJ per day all year around, and also with the assumption that the system requires 3.5 MJ to evaporate 1 kg of water from a paper, and that an average paper holds between 0.248 kg (cotton) and 0.412 kg (jute), one such collector can dry between 6 530 and 10 850 papers each year.

7.3.4 ENERGY LOSSES DURING THE NIGHT

The system constructed could be used to dry papers long after sunset, but the drying time increased with reduced temperature of the DP. Thus there came a point when drying was stopped, either due to the late hour, or due to the long drying time, but at which point not all energy absorbed by the collector had been used to dry papers.

This made it possible to store energy from one day to the other. But a system designed to transfer as much energy as possible from the water inside to the surroundings, will also have high system losses during the night. Still the heat loss from the DP could be as low as 1.3°C per hour (when not much heat is stored in the drier plate), but was usually around 2.5°C per hour. But the manifold of the solar collector is made out of insulating materials, and the absorber tubes have a vacuum that insulates the water inside from direct thermal contact with the surrounding air. Therefore it was a much better storage for the extra energy that had not been used at the end of a day. Thus the heat losses from the SC were only between 1.1°C to 1.6°C per hour.

As an example, on the night between the 3rd and the 4th of February (seen in Figure 49 below), where data were recorded at four different positions inside the tank of the collector during the whole night – it is very clear that the temperature inside the SC (red, purple, orange and dark blue lines) drops much slower than the temperature in the drier plate (green line). So, even if energy is lost over night from the system, still the temperature in both the DP and the SC is higher than the ambient temperature when the pump was turned on the next morning. Also it is clear that the top and bottom of the SC cools down more than the two measurement points inside the manifold. Also as the biggest mass of water is contained inside the collector, the biggest amount of energy would also be stored there, thus the conclusion is that a big amount of energy can be stored from one day to the next using this system.

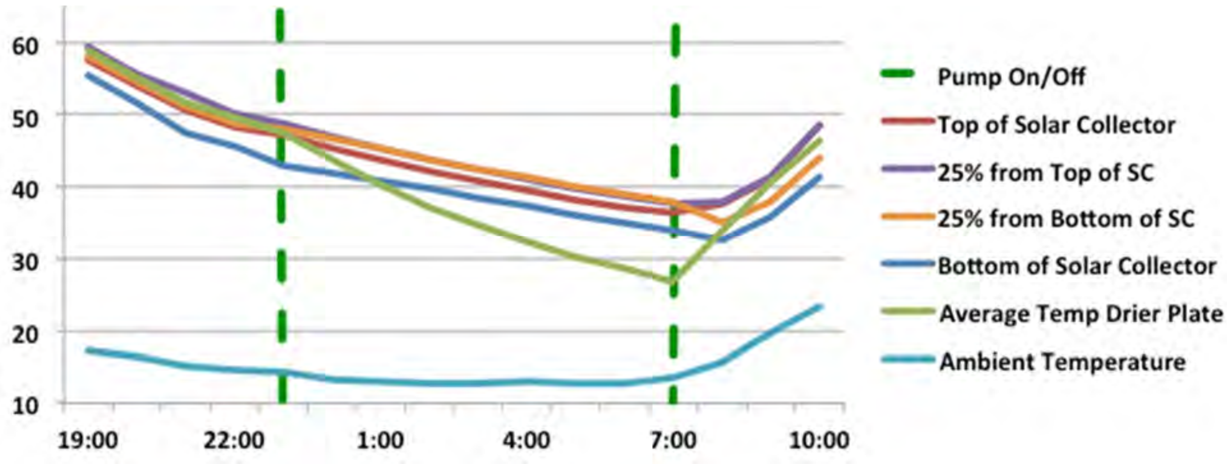

FIGURE 49 TEMPERATURE DROP INSIDE THE TANK OF THE SOLAR COLLECTOR VERSUS THE AVERAGE TEMPERATURE OF THE DP AS WELL AS THE AMBIENT TEMP BETWEEN THE 3RD AND 4TH OF FEBRUARY. THE GREEN DASHED LINE INDICATING THE TIME WHEN THE PUMP WAS TURNED ON AND OFF

7.4 SAVINGS WITH THE COLLECTOR

Finally some results in regards to the economic benefits of continuing this program are examined. But to calculate the economic return of the collector, a few assumptions and facts need to be put forth:

1. Assuming that the collector will deliver 25.8 MJ of useful energy each day.
2. Assuming this hot water can dry papers at an efficiency of 3.5 MJ per kg water evaporated.
3. Using the assumption that a 16 ft. drier (using the old system) on average evaporates 50 kg of water each day (Thomas, 2010).

To replace such a drier, the new system needs to generate 175 MJ of drying power each day, thus on average 6.8 collectors (with an aperture area of 34 m^2) are needed to replace one 16 ft. drier.

To buy one collector including the shipping from China to Bangladesh ended up to $385 (or 31 570 Tk) (Sunsurf, 2010). Thus seven collectors could cost up to 220 990 Tk. This is to be compared with the annual cost of fuel for a “big” 16 ft. drier, which is 90,000 Tk. It is clear that the collectors would repay themselves in as little as 2.5 years if they would be usable all year long. As the collectors might be less usable during the rainy season and at days with poor weather, the payback time might increase to maybe 3 or in the worst case 5 years.

On the other hand, as the new system is a closed loop, the amount of new oxygen added to the system is very limited. This results in a steady state at some point when all the free oxygen in the water has reacted with the metals in the DP, which means that after a while the corrosion will stop completely. This gives the system a much longer lifetime and reduces cost for reparations and buying a new drier every 20 months (estimated saving of about 23 000 Tk per year).

All in all this results in the solar collectors being a very good investment seen over a few years, and considering an expected lifetime of 15 years, or even 20 or 25 years for the collectors, the investment looks very promising.

8 CONCLUSIONS AND FURTHER RESERCH

The conclusions from this study are that the solar collector used could absorb over 70% of the incoming radiation and turn it into hot water. When comparing the new system with the old system, an increased efficiency of at least 40% can be expected by changing to the new setup. Looking only on the efficiency of the drier plate resulted in an energy requirement of 3.5 MJ to evaporate 1 kg of water from the paper being dried. Also from an economical perspective this study does indicate a good payback time and real improvement of the finances of the drying process, mostly due to the high fuel cost in the current system.

To confirm these results, a study with a bigger Drier Plate should be conducted to continue investigate this design. And in the end of this paper there are some suggestions for what parameters a follow up on this study could focus on. For instance would it be very interesting to investigating the impact of the airflow around the paper in combination with this design. As well as a study on how the flow rate of the water can be optimized in relation to the thickness of the drier plate.

8.1 CONCLUSIONS REGARDING THE COLLECTOR

Summarizing the output from this study it was clear that the evacuated collector design is a good choice for this type of application. The biggest drawbacks are the big land area that the collector will require, and that drying will be most efficient in afternoons and evenings, instead of mornings. As many of the workers in Bangladesh are used to start the day early and then go home before it gets dark, this might take some time to get used to.

Looking on the conversion rate, the collector had an efficiency of 71% as seen in section 7.3.3 Conversion efficiency of the collector. This is a good efficiency on par with other similar systems. On the other hand only about half of the converted energy was then used to dry papers, and the rest was lost due to system losses. But this value varied a lot with the usage of the system, so on a day when the usage of the dryer was high, the efficiency also increased. While on a day when the system was not used as frequently to dry papers, more energy was lost in the form of system losses.

8.1.1 CONCLUSIONS REGARDING THE DRIER PLATE AND THE SYSTEM

From the study it was also clear that the energy required to dry a paper was not dependent on the fiber type, the water content of the paper or the temperature of the drier plate. This value was instead only dependent on the efficiency of the system. The drying time on the other hand was strongly linked to both the temperature of the DP and the water content of the paper before drying. It was therefore possible to determine that the new system used 4.8 MJ to evaporate 1 kg of water from the drying papers independent of the temperature of the DP. Thus the new system was 40% more efficient than the old system (when comparing the efficiency including the system losses for both systems).

Because the system losses depended on how big part of the day the system that was used to dry papers, how well insulated the piping was, and the ambient conditions such as temperature and wind speed; it was also interesting to look only at the drier plate on its own. Thus not including the change in energy in the rest of the system. When doing so the result showed that the DP extracted on average 3.5 MJ from the water circulating through it in order to evaporate 1 kg water from the papers. To get a feeling for how efficient this is, the value can be compared with the 2.6 MJ that is the theoretically minimum energy required to turn 1 kg of water into steam (when the water has a starting temp of 10°C).

8.1.2 CONCLUSIONS REGARDING THE ELECTRIC WATER HEATER

The electric water heater was not part of the original setup, but was a very valuable complement to the solar collector, as it helped develop the whole system even before we got hold of the solar collector. Once the collector arrived it was very easy to replace the EWH with the SC. This gives an indication that the setup should be easy to adapt to have an auxiliary system as backup no matter whether that system is powered by electricity, gas or firewood, as long as it can deliver hot water in a tube, it can be connected in series after, or in parallel with the collector. Another conclusion could be that even if the solar collector would not be included in the loop, a change to a system where the heat carrier is water instead of an air-steam mixture should be beneficial. The only drawback with the new setup would be a dependence on electricity for circulating the water, but with the modern UPS-systems this is not regarded a big problem.

8.1.3 OUTPUT OVER A WHOLE YEAR

To make predictions on how well this system would perform over a full year, the average of the measured solar radiation that did hit the collector during the testing period (16.1 MJ/m^2) were compared with the SWERA-data. When calculating the average irradiation of January and February, the SWERA-data predicted that the collector would have been exposed to about 15.6 MJ/m^2. It is thus clear that the SWERA-data hold up really well for this application.

According to the SWERA data, the energy hitting the collector each day (average over a full year) will be about 17.2 MJ/m^2. So, for a collector with an aperture area of 5 m^2, an average of 86 MJ will be hitting the collector each day. Based on the conversion efficiency of the collector, it will on average absorb 61 MJ of this energy and be able to use 26 MJ to dry papers each day. With the assumption that an average paper hold between 0.248 kg (cotton) to 0.412 kg (jute), the collector used in this tests should be able to dry between 6 530 and 10 850 papers each year, when a paper usually is about 55-60 cm wide and about 80-90 cm high.

8.1.4 DRYING SHIFTED TO AFTERNOONS AND EVENINGS

As mentioned above one of the few drawbacks with the system, was the long startup time in the morning as the collector contained a lot of water. Even with the tilted design that ensured that the hottest water naturally flowed to the top, where the outlet was placed, the water leaving the collector, the DP reached 45°C around 10:00 and 55°C around 11:00 in the morning. This is very much dependent on the fact that the solar radiation is not constant over the day. Instead most energy hit the collector around midday, and with the delay from the time when the energy hit the collector until it is extracted, the most efficient use of the dryer will be from midday and into the evening.

This calls for an auxiliary energy source to be used in the morning hours, or to shift the working hours for drying to later in the day. If this shift can be agreed with the workers, it is still possible to have a full day of drying with the dryer, as can be seen from the data collected on the 31st of January. On this day 19 papers were dried starting from 10 am, when the average temperature of the drier plate had reached 44°C. Papers were then dried during the whole day, with a maximum temperature of 71°C, until 20:40 in the evening at which point the temperature of the drier was back down at 49°C. Thus it would still be possible to have a functional drying process for about 8-10 hours each day.

8.2 CONCLUSIONS ABOUT COSTS

The cost of a 5 m^2 collector is about 30% more than an old 16ft. drier and about twice the cost of a 8 ft. drier, but as the big cost with the old system is the cost of fuel, that needs to be included as well. When doing so the payback period for replacing a 16 ft. drier with collectors is between 2 to 5 years depending on how many days of the year the collectors can deliver the expected 26 MJ of useful drying power each. A bigger study should be done to follow up on this one to confirm these data, but the initial calculations indicate that it should be very beneficial to move to solar heated driers.

Another benefit is that the closed loop created in the system, when using water as the heat carrier, limits the amount of oxygen added to the system, and thereby also the corrosion inside the system. This gives the system a much longer lifetime and reduces cost for reparations. Due to the lower risk for corrosion, normal steel can be used instead of stainless steel, which also lower the cost of production in the first place. This way the initial cost can be kept down and there is no need to replace the drier every two years, as the expected lifetime will increase. Exactly how much longer the lifetime may become needs to be investigated further as it also depends on the corrosion on the outside of the drier.

8.3 UNCERTAINTIES IN THE MEASUREMENTS

8.3.1 UNCERTAINTIES DUE TO THE HUMAN FACTOR

The biggest errors have most likely been due to the human factor and also the short amount of time with the collector that made it hard to conduct the same tests again after fixing some problem that occurred or a change in the setup. Some examples of the human factor that can have affected this were when measuring the weight of the papers before and after each drying test. This required an accurate scale and good weighing conditions. There was a scale available that could do this job well but the conditions for weighing could have been improved even more.

To protect the papers and the scale during the weighing of a wet paper before drying, all papers were weighed inside the workshop too keep the setup protected from the wind. The reason for this was that the papers were quite big and the wind easily pushed them up and down as it passed the papers. Unfortunately the entrance to the workshop was quite big, so even with walls protecting the setup in three directions, the wind can still have affected this measurement a bit. Resulting in a lower weight when the wind created a lift, and a bigger weight when it pushed the paper down towards the scale. To minimize this error the same person did all measurements and they were all conducted under the same conditions, so at least the systematic error should be as similar as possible for all measurements.

Another uncertainty due to the way measurements were collected was the measurement of the time it took to dry a paper, as it has only been measured on a minute level. This was not a problem at lower temperatures but at the higher temperatures when a paper could be dried in less than 10 min it can have resulted in as much as 20% off the correct time. To reduce this error an on-off switch was introduced to be toggled each time a paper was added or removed from the DP, but as the data logger also only saved an average of each min, an error of about 10% can still be possible here for drying at higher temperatures.

8.3.2 UNCERTAINTIES DUE TO OTHER FACTORS

Some of the problems were not due to human error, but rather the lacking resources available at the center. On such limitation was the lack of newly produced papers, so a system for remoistening dried papers was used instead. And even if the way papers were re- moistened was considered smart and well planned, it could be a problem that the paper was re-wetted instead of dried from wet pulp. This way the newly added water can have entered the inter-fiber pores in the paper without entering into the intra-fiber pores. As the water between the fibers is easier to remove than the water inside the fibers, this could result in an over-estimation in the efficiency of the drying process.

Also, for some reason that never got solved completely, some type of leak current did offset the data from the thermo couples on the drier plate if this insulation was not applied. Thus if a TC slid out of the insulating tape (that had been used to keep the two surfaces electrically separated but in thermal contact), the data from that TC turned out to be totally wrong. Values such as negative temperatures or just a very big or small value were recorded. The value was always clearly wrong and therefore quite easy to spot as long as someone was supervising the setup. But sometimes it could take up to two hours before someone noted that a TC was wrong, thus losing all data from that spot on the DP for the period with faulty values. The solution for this was in most cases to simply delete the measurements that were wrong as the only value used was the average of the nine thermo couples, but none of the tests with a lot of missing data have been included in the results of this study.

Finally, one measuring error in this study may have been the definition in section 5.3.2 Compensation for energy stored inside the DP where the change in stored energy inside the Drier Plate was defined as:

$$\Delta \boldsymbol{E}_{\boldsymbol{Stored\ in\ DP}} = \boldsymbol{m}_{\boldsymbol{Water\ in\ DP}} \cdot \boldsymbol{C}_{\boldsymbol{P,Water}} \cdot (\boldsymbol{T}_{\boldsymbol{TCs\ after\ drying}} - \boldsymbol{T}_{\boldsymbol{TCs\ before\ drying}})$$

The average of the inlet and the outlet temperature could have been a better value to use as the TCs were moved around a bit (first from the front to both the front and the back and finally to only the back of the Drier Plate). Some tests have been made where the average of the water temperature has been used instead to compare – and at times the difference in estimated stored energy can be as big as 27% more energy stored. This then resulted in a reduced efficiency of 9% for the DP and 8% for the whole system. The reason for this difference is still not clear for all occasions, as the same comparison at other times resulted in 4% less energy stored, which then resulted in a 4% more efficient DP and a 3% more efficient system as a whole. The initial calculations indicated that the more conservative value was achieved by using the average of the TCs compared to the average of the water temperature entering and leaving the DP, but later calculations are not consistent with this statement. In the end the general conclusions made from the drying tests are regarded useful for the conclusions drawn from the study, even if these data have not been recalculated in the way suggested above.

8.4 SUGGESTIONS FOR FUTURE RESEARCH

As this was conducted as an initial study to investigate the possibility to replace all driers with solar heated driers, a natural next step would be to build a full scale drier using the data gathered in this study as a base. It would be interesting to see if the collector can supply a bigger Drier Plate, and if not, how to connect several collectors to gain maximum efficiency? Also it would be interesting to further investigate the theory that the system losses will become a smaller part of the total energy in a bigger system.

Another test would be to build a passive testing area where the energy generated by the collector could be dumped in some type of heat sink. The benefit with this setup is that data can be gathered about the conversion efficiency of the system over a longer period without the need to actively engaging in the testing. The idea would be to monitor the energy dumped in the heat sink to gather data regarding how much energy the collector actually can produce over a year. This type of study should ideally be conducted at one of the paper-producing sites, in order to gather data about the location at the same time.

Another important parameter that has been totally left out in this study is the airflow passing the paper. This can have had an impact at the drying time, especially during the tests when the solar collector was used as the heat source, as those tests were conducted outside. It could therefore be very interesting to investigate the impact of the airflow around the drier plate. As an increased airflow both transport away more moisture and cool down the paper, it is not clear if this would increase or decrease the efficiency of the system. That would depend on which parameter that has the biggest effect. And does this depend on the ambient humidity and temperature? This could possibly be studied by building a small house with removable walls. The walls could then be added or removed depending on the conditions. For instance it could be interesting to have walls during the rainy season as one does not want rainwater to wet the papers, but at the same time it would be good to increase the convection during the drier months and on hot days.

Finally an interesting test to conduct would be to produce a few different drier plates with different width and then try to find an optimal level of the water flow in the system in relation to this width. As the water in a thinner DP can be replaced faster, that might enable a faster start-up time in the mornings. On the other hand a thin DP will result in a bigger temperature difference between the water entering and the water leaving the drier. Thus, if the DP would be very long (to fit several papers after each other) the temperature from one paper to the next would vary more. Or, depending on how the construction is made, the temperature from the top to the bottom of each paper would vary more. On the other hand, that effect can be reduced by increasing the flow rate through the DP. But with a too high flow the water on the cold side of the loop would be higher and thus the system losses increase. So it would be interesting to find the optimal balance between these two parameters.

ACKNOWLEDGEMENTS

This project was performed in cooperation Daniel Thomas, and the rest of the wonderful team working at MCC's center for development of sustainable technology in Bogra in the time period of November 2010 to February 2011. Without the guidance and resourcefulness of Mr. Thomas this project would not have been completed nearly as well as it has. I also want to thank Lokhan Paul for his substantial contributions to this project. Without his help I would not have been able to obtain the material needed to build the system. Mr. Lokhan also helped in guiding me to skilled craftsmen in the area that could help with specific tasks such as sealing the leaking Drier Plate with the help of gas welding.

On top of this I also want to thank Nathan Charles that also have guided me and been a good companion on site during my stay. His knowledge in the solar field has been useful during the research relevant theories needed for writing this thesis.

Finally among my local friends and colleges contributing to this study I want to give a big thanks to Iqbal Hussain, Swapan Kumar Das and Rana Masud that all has contributed with important knowledge about MCC, Prokritee and the state of electricity generation in Bangladesh. This has added to my understanding of the history of the production of handmade paper in this region. I also want to thank MCC and Prokritee as organizations for their financial contribution in buying the material used as well as providing me with accommodation during my stay in the country.

But to draw the correct conclusions from a study like this, it is important to also have the right theories to base the analysis around. I therefore once again want to thank Mr. Thomas for his help, but this time for the guidance and perseverance during my writing of this paper. During this time I also have had great support from Ewa Wäckelgård and Ingvar Backeus that have read and re-read several of my drafts and guided me during this whole process. Without their support and encouragement this thesis might have taken even longer to be completed and especially thanks to Ewa that managed to draw my attention to the lack of compensation of ground reflection in my initial calculations. This finding led me to re-write a big part of the theory section related to the absorption capacity of the collector.

I also want to thank Uppsala University for their excellent course in Solar Energy – Technology and Systems as well as Högskolan Dalarna for their excellent courses in Solar Thermal Energy, with a special focus on Solar Thermal in Hot Climates. These courses have all helped me a much better theoretical foundation for the conclusions made in this study.

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TABLE OF FIGURES

APPENDICES

APPENDIX A: ABBREVIATION

TABLE 4: ABBREVIATIONS USED IN THIS THESIS

ABBREVIATION	EXPLANATION
SC	Solar Collector
EWH	Electric Water Heater
DP	Drying Plate
HS	Horizontal Setup
VS	Vertical Setup
TCs	Thermocouples

APPENDIX B: DATA FROM SWERA

The Solar and Wind Energy Resource Assessment (SWERA) project was started with funding from Global Environment Facility (GEF) in 2001 and from the start managed by the United Nations Environment Programme's (UNEP) Division of Technology, Industry and Economics (DTIE) where it expanded into a full program in 2006. (OpenEI, u.d.) The data used to create the solar maps and have been compiled by SWERA but comes from data measured by several groups such as NREL (National Renewable Energy Laboratory in USA), DLR (German Aerospace Center in Germany) and RERC (Renewable Energy Research Centre at the University of Dhaka in Bangladesh). RERC has been the local country partner in Bangladesh and thereby a big contributor to compiling this data and make it usable to independent reaches. Many of the data sets come from time periods and have been collected with different methods. Therefor only averages on a monthly and yearly basis have been used.

APPENDIX C: WEIGHT OF EQUIPMENT USED- SUMMARY

Electric Water Heater (EWH)		
Weight of EWH:	16,8	kg (without water)
Amount of water in EWH:	30	Liter
Weight of water in EWH:	29	kg

Drying Plate (DP)		
Weight of DP:	19,1	kg (without water)
Weight of water in DP:	27,2	kg
Weight of water in tubes, pump and filter:	1-2	kg

Solar Collector (SC)		
Area		
Gross area	7,3	m2 - 374x194 cm gross area (manifold 194 cm long).
Gap between two tubes	1,5	cm
Tube outer diameter	5,8	cm
Tube inner diameter	4,7	cm
Top tube to bottom tube ca	180	cm
Inside of endcap to manifold	173	cm (west side)
(i.e. lengt of tube exposed to sun)	172	cm (east side)
=> Apareture area	5,0	m2
=> Apareture area per Tube	0,1	m2
From manifold to silver area	169	cm (west side)
(i.e. lengt of tube absorbing heat)	168	cm (east side)
=> Absorber area	4,0	m2
=> Absorber area per Tube	0,08	m2
Volume		
Cross section of inner tube	0,0017	m2
Volume water in one tube	3,0	liter
Volume in Manifold	59,7	liter
Volume in Total	211	liter

APPENDIX D: WEIGHT OF PAPERS - SUMMARY

TABLE 5: SHORT LIST OF PAPERS USED IN RECORDED DRYING TESTS. ONLY CONSIST OF TYPE, WEIGHT AND WEIGHT DISTRIBUTION.

Type of paper	Paper #	Dry weight (kg)	Times dried	Average wet weight (kg)	+/- (% / g)	Av. Weight after drying (kg)	+/- (% / g)
Cotton	CX	0.110	4	0.363	4.1% / 15	0.133	15.1% / 20
	C1	0.120	3	0.367	3.4% / 12.5	0.118	2.1% / 2.5
	C2	0.135	4	0.388	7.2% / 28	0.148	8.5% / 12.5
	C3	0.115	4	0.334	3.7% / 12.5	0.126	13.9% / 17.5
	C4	0.150	3	0.418	0.6% / 2.5	0.150	5.0% / 7.5
	C5	0.145	1	0.430	0.0% / 0	0.170	0.0% / 0
	C6	0.130	13	0.395	6.3% / 25	0.137	21.9% / 30
	C7	0.135	1	0.350	0.0% / 0	0.130	0.0% / 0
	C8	0.160	6	0.447	6.2% / 27.5	0.175	5.7% / 10
	C9	0.140	9	0.396	5.7% / 22.5	0.152	18.1% / 27.5
	C12	0.140	1	0.345	0.0% / 0.0	0.165	0.0% / 0
Jute	J1	0.120	5	0.529	1.4% / 7.5	0.123	12.2% / 15
	J2	0.130	7	0.559	5.8% / 32.5	0.131	11.4% / 15
	J3	0.135	11	0.573	6.5% / 37.5	0.145	13.8% / 20
	J4	0.155[dd]	3	0.652	0.4% / 2.5	0.152	4.9% / 7.5
	J6	0.130	9	0.539	1.9% / 10	0.211	74.6% / 157.5
	J7	0.135	1	0.555	0.0% / 0	0.160	0.0% / 0
	J8	0.135	4	0.531	3.3% / 17.5	0.146	12.0% / 17.5
	J11	0.105	1	0.420	0.0% / 0	0.095	0.0% / 0
Straw	S1	0.120	1	0.495	0.0% / 0	0.155	0.0% / 0
	S2	0.120	2	0.498	0.5% / 2.5	0.120	8.3% / 10
	S3	0.115	4	0.456	0.5% / 2.5	0.133	7.5% / 10
	S4	0.115	3	0.458	1.6% / 7.5	0.130	5.8% / 7.5

TABLE 6: PAPERS NOT USED IN RECORDED DRYING TESTS

Paper #	Dry weight (kg)	Times dried
C10	0.155	0
C11	0.150	0
J5	Unknown	0
J9	0.155	0
J10	0.145	0
J12	0.115	0

Size
All papers are less than 60x90 cm
Some are down to 55x80 cm

The time it took for a paper to dry was noted down by marking the time (hh:mm) when the paper was put on the DP and again the time (hh:mm) when the paper was taken off. Because the time was not noted down on a second level an error of up to up to 59 seconds exists for both measurement points. This wasn't significant at early dryings where the average temperature in the DP was lower and therefore resulted in longer drying times. At higher temperature the drying times went down as low as 6 min, where in worst case an error of 1 minute and 58 seconds in percentage turn into an error of +/- 15 %. This can especially influence the "Energy used for drying (MJ / kWh)" and then also the "Drying energy [MJ/kg,water]".

TABLE 7: EXPLANATORY COMMENTS ON HEADINGS IN TABLE 8 AND TABLE 9

	EXPLANATION OF HEADINGS IN TABLE 8 AND TABLE 9
Drying #	SC = Solar collector, SC1 = First paper dried with Solar Collector, EWH = Electric Water Heater
Paper #	Each paper was marked with a number 1-12 for each type of paper respectively. C1 = Cotton paper #1, J = Jute and S = Straw. In the experiment a total of 12 cotton papers, 11 jute papers and 3 straw papers was included.
Type of paper	Cotton, Jute or Straw
Dry weight (kg)	Before the paper was wetted it was weighted on a scale.
Wet weight (kg)	After paper being wetted it was weighted on the same scale as the dry paper.
Before dry. (%MC,wb)	This value is the Wet-basis Moisture Content – after paper was wetted but before drying. Calculated with Wet weight and Dry weight.
After dry. (%MC,wb)	This value is the Wet-basis Moisture Content – after the paper was dried. To calculate this, the dried paper was weighted a third time.
Drying time (min)	Time from paper was put on DP until it was taken of the DP (or fell off by itself)
Energy used for drying (MJ / kWh)	Sum up of all energy added to DP during drying minus the energy been stored in the water in the DP during the same time. Presented both in MJ and kWh.
Drying energy [MJ/kg,water]	Energy used to dry the paper (MJ/kg,water) where (MJ) = energy added to the DP during the drying time and (kg,water) = kilos of water evaporated from the paper during the drying time
Average DP temp. (°C)	The average of (T_{W2}) and (T_{W3}). Where (T_{W2}) is the average temperature of the water coming into the DP and (T_{W3}) is the average temperature of the water leaving the DP during the drying time. Many other ways of estimating this temperature could be done but the only reasonable parameter that was constantly measured in the same way during all tests was (T_{W2}) and (T_{W3}). This value can then be compared and analyzed with other temperature measurements for individual tests.

TABLE 8: LIST OF PAPERS DRIED WITH ELECTRIC WATER HEATER (EWH) – USABLE DATA

Date	Drying #	Paper #	Type of paper	Dry weight (kg)	Wet weight (kg)	Before dry. (%MC,wb)	After dry. (%MC,wb)	Drying time (min)	Energy used for drying (MJ / kWh)	Drying energy [MJ/kg,water]	Average DP temp. (°C)
2011-01-19	EWH 3	CX[r]	Cotton	0.110[s]	0.380	71.1 %	8.3 %	29	0.753 / 0.21	2.90	59.8°
	EWH 4	CX[r]	Cotton	0.110[s]	0.355	69.0 %	12.0 %	16	0.861 / 0.24	3.75	66.2°
	EWH 7	C2	Cotton	0.135	0.385	64.9 %	10.0 %	22	0.994 / 0.28	4.23	64.1°
	EWH 8	C1	Cotton	0.120	0.355	66.2 %	0.0 %	18	1.072 / 0.30	4.56	65.9°
	EWH 9	C2	Cotton	0.135	0.390	65.4 %	6.9 %	17	0.820 / 0.23	3.35	67.0°
	EWH 11	J1	Jute	0.120	0.525	77.1 %	4.0 %	33	1.663 / 0.46	4.16	65.7°
	EWH 12	J2	Jute	0.130	0.590	78.0 %	**-8.3 %**	35	2.142 / 0.60	4.56	67.4°
	EWH 13	J1	Jute	0.120	0.530	77.4 %	0.0 %	39	1.791 / 0.50	4.37	65.1°
2011-01-20	EWH 16	J1	Jute	0.120	0.540	77.8 %	0.0 %	37	1.377 / 0.38	3.28	65.5°
	EWH 17	J2	Jute	0.130	0.545	76.1 %	0.0 %	36	1.524 / 0.42	3.67	68.9°
	EWH 18	C2	Cotton	0.135	0.415	67.5 %	0.0 %	24	0.924 / 0.26	3.30	65.8°
	EWH 19	C1	Cotton	0.120	0.380	68.4 %	**-4.3 %**	19	0.965 / 0.27	3.64	67.3°
	EWH 20	J1	Jute	0.125	0.525	76.2 %	10.7 %	27	1.721 / 0.48	4.47	68.5°
	EWH 22	C5	Cotton	0.145	0.430	66.3 %	14.7 %	17	0.870 / 0.24	3.35	67.1°
	EWH 23	C8	Cotton	0.160	0.445	64.0 %	13.5 %	20	1.093 / 0.30	4.20	64.9°
2011-01-23	EWH 24	C6	Cotton	0.130	0.380	65.8 %	**27.8%**	62	0.872 / 0.24	4.36	39.2°
	EWH 25	C6	Cotton	0.130	0.385	66.2 %	13.3 %	34	1.121 / 0.31	4.77	48.5°
2011-01-24	EWH 26	C6	Cotton	0.130	0.370	64.9 %	3.7 %	29	0.846 / 0.23	3.60	53.5°
	EWH 27	C6	Cotton	0.130	0.375	65.3 %	0.0 %	24	0.884 / 0.25	3.61	58.1°
	EWH 28	J2	Jute	0.130	0.560	76.8 %	7.1 %	46	1.441 / 0.40	3.43	57.9°
	EWH 29	C6	Cotton	0.130	0.390	66.7 %	7.1 %	21	0.834 / 0.23	3.33	62.9°
	EWH 31	C6	Cotton	0.130	0.400	67.5 %	3.7 %	21	0.865 / 0.24	3.27	62.1°
	EWH 32	C6	Cotton	0.130	0.400	67.5 %	0.0 %	18	0.906 / 0.25	3.35	66.6°
	EWH 33	J2	Jute	0.130	0.560	76.8 %	**-4.0 %**	32	1.545 / 0.43	3.55	66.3°
	EWH 34	C6	Cotton	0.130	0.400	67.5 %	**-4.0 %**	17	0.935 / 0.26	3.40	66.8°
2011-01-25	EWH 35	J6	Jute	0.130	0.535	75.7 %	**18.8 %**	31	1.164 / 0.32	3.10	64.4°
	EWH 36	J6	Jute	0.130	0.535	75.7 %	3.7 %	29	1.351 / 0.38	3.38	68.4°
	EWH 37	C6	Cotton	0.130	0.400	67.5 %	0.0 %	17	0.890 / 0.25	3.30	68.0°
2011-01-26	EWH 38	C6	Cotton	0.130	0.400	67.5 %	7.1 %	52	0.843 / 0.23	3.24	44.3°
	EWH 40	J6	Jute	0.130	0.530	75.5 %	**23.5 %**	79	1.113 / 0.31	3.09	44.7°
2011-01-27	EWH 42	J6	Jute	0.130	0.550	76.4 %	**16.1 %**	70	1.460 / 0.41	3.70	49.1°
	EWH 43	C9	Cotton	0.140	0.380	63.2 %	**17.6 %**	34	0.789 / 0.22	3.76	49.7°
	EWH 44	J6	Jute	0.130	0.550	76.4 %	13.3 %	51	1.376 / 0.38	3.44	54.0°
	EWH 45	C4	Cotton	0.155	0.420	64.3 %	**-3.4 %**	37	0.942 / 0.26	3.43	54.0°

TABLE 9: LIST OF PAPERS DRIED WITH THE SOLAR COLLECTOR (SC)

Date	Drying #	Paper #	Type of paper	Dry weight (kg)	Wet weight (kg)	Before dry. (%MC_{wb})	After dry. (%MC_{wb})	Drying time (min)	Energy used for drying (MJ / kWh)	Drying energy [MJ/kg,$_{water}$]	Average DP temp. (°C)
2011-01-30	SC 1	C4	Cotton	0.150	0.415	63.9 %	**-3.4 %**	15	0.894 / 0.25	3.31	71.7°
	SC 2	J4	Jute	0.155	0.655	76.3 %	3.1 %	29	1.439 / 0.40	2.91	67.1°
	SC 3	C8	Cotton	0.160	0.420	61.9 %	11.1 %	18	0.860 / 0.24	3.58	65.2°
	SC 4[p]	J4	Jute	0.155	0.650	76.2 %	**-6.9 %**	43	1.578 / 0.44	3.13	63.5°
2011-01-31	SC 5	C9	Cotton	0.140	0.370	62.2 %	**20.0 %**	33	0.617 / 0.17	3.16	44.4°
	SC 6	J2	Jute	0.130	0.525	75.2 %	13.3 %	56	1.284 / 0.36	3.42	47.6°
	SC 7	C9	Cotton	0.140	0.400	65.0 %	3.4 %	27	0.903 / 0.25	3.54	52.7°
	SC 8	J6	Jute	0.130	0.535	75.7 %	**18.8 %**	30	1.194 / 0.33	3.18	57.9°
	SC 9	J3	Jute	0.135	0.515	73.8 %	**18.2 %**	27	1.296 / 0.36	3.70	62.8°
	SC 10	J3	Jute	0.135	0.585	76.9 %	**15.6 %**	31	1.434 / 0.40	3.37	66.6°
	SC 11	J6	Jute	0.130	0.540	75.9 %	7.1 %	20	1.243 / 0.35	3.11	68.8°
	SC 12	C8	Cotton	0.160	0.435	63.2 %	5.9 %	14	0.870 / 0.24	3.28	69.8°
	SC 13[q]	C9	Cotton	0.140	0.390	64.1 %	**26.3 %**	13	0.659 / 0.18	3.29	70.3°
	SC 14	J3	Jute	0.135	0.590	77.1 %	**15.6 %**	21	1.280 / 0.36	2.98	69.9°
	SC 15	C8	Cotton	0.160	0.445	64.0 %	8.6 %	14	0.886 / 0.25	3.28	68.9°
	SC 16	C9	Cotton	0.140	0.400	65.0 %	**-3.7 %**	16	0.873 / 0.24	3.29	68.2°
	SC 17	J3	Jute	0.135	0.585	76.9 %	12.9 %	27	1.418 / 0.39	3.30	66.7°
	SC 18	C9	Cotton	0.140	0.415	66.3 %	0.0 %	21	0.903 / 0.25	3.28	64.7°
	SC 19	C6	Cotton	0.130	0.400	67.5 %	0.0 %	22	0.860 / 0.24	3.18	62.5°
	SC 20	C3	Cotton	0.115	0.330	65.2 %	0.0 %	20	0.747 / 0.21	3.47	60.4°
	SC 21	J3	Jute	0.135	0.580	76.7 %	6.9 %	48	1.589 / 0.44	3.65	57.2°
	SC 22	C6	Cotton	0.130	0.410	68.3 %	3.7 %	31	1.015 / 0.28	3.69	53.4°
	SC 23	J3	Jute	0.135	0.585	76.9 %	10.0 %	72	1.806 / 0.50	4.15	49.7°
2011-02-01	SC 24	J3	Jute	0.135	0.550	75.5 %	0.0 %	16	1.333 / 0.37	3.21	81.1°
	SC 25	J8	Jute	0.135	0.550	75.5 %	0.0 %	14	1.253 / 0.35	3.02	83.1°
	SC 27	J3	Jute	0.135	0.575	76.5 %	0.0 %	14	1.377 / 0.38	3.13	84.9°
	SC 28	C8	Cotton	0.160	0.475	66.3 %	3.0 %	13	1.270 / 0.35	4.10	84.8°
	SC 29	J3	Jute	0.135	0.575	76.5 %	**-8.0 %**	14	1.743 / 0.48	3.87	84.8°
	SC 30	C7	Cotton	0.135	0.350	61.4 %	**-3.8 %**	9	0.930 / 0.26	4.23	85.1°
	SC 31	J3	Jute	0.135	0.580	76.7 %	3.6 %	13	1.665 / 0.46	3.78	84.5°
	SC 32	J7	Jute	0.135	0.555	75.7 %	15.6 %	15	1.403 / 0.39	3.55	83.5°
	SC 34	J4	Jute	0.150	0.650	76.9 %	0.0 %	21	1.840 / 0.51	3.68	81.5°
	SC 35	C3	Cotton	0.115	0.330	65.2 %	4.2 %	15	0.916 / 0.25	4.36	80.3°
	SC 36	J1	Jute	0.120	0.525	77.1 %	**-9.1 %**	22	1.490 / 0.41	3.59	78.5°
	SC 37	C6	Cotton	0.130	0.420	69.0 %	**-8.3 %**	15	1.068 / 0.30	3.56	75.8°
	SC 38	J3	Jute	0.135	0.580	76.7 %	**-8.0 %**	25	1.623 / 0.45	3.57	72.7°
2011-02-02	SC 39	C12	Cotton	0.140	0.345	59.4 %	**15.2 %**	13	0.607 / 0.17	3.37	71.5°
	SC 40	J11	Jute	0.105	0.420	75.0 %	**-10.5 %**	23	1.154 / 0.32	3.55	68.4°

[p] A corner of the paper was tiered off when moving the wet paper to the DP, the mass loosed is not estimated more than 5-10 g, but might have a slight impact on this measurement.
[q] Paper fell of the DP by it self before completely dry. (%MCwb) = 26.3 % after drying.

	SC 41	S2	Straw	0.120	0.500	76.0 %	7.7 %	27	1.271 / 0.35	3.43	66.0°
	SC 42	C9	Cotton	0.140	0.400	65.0 %	0.0 %	20	0.879 / 0.24	3.38	63.5
	SC 43	J8	Jute	0.135	0.525	74.3 %	**20.6 %**	36	1.361 / 0.38	3.83	60.1°
	SC 44	S2	Straw	0.120	0.495	75.8 %	**-9.1 %**	51	1.634 / 0.45	4.24	55.8°
	SC 45	S3	Straw	0.115	0.460	75.0 %	11.5 %	51	1.465 / 0.41	4.44	53.1°
2011-02-03	SC 46	S3	Straw	0.115	0.455	74.7 %	**17.9 %**	14	0.927 / 0.26	2.94	80.6°
	SC 47	J8	Jute	0.135	0.515	73.8 %	0.0 %	18	1.333 / 0.37	3.51	79.4°
	SC 48	C9	Cotton	0.140	0.400	64.0 %	-3.7 %	12	0.981 / 0.27	3.70	78.4°
	SC 49	S3	Straw	0.115	0.455	77.7 %	**17.9 %**	13	0.883 / 0.25	2.80	77.7°
	SC 50	J8	Jute	0.135	0.535	74.8 %	6.9 %	16	1.176 / 0.33	3.01	76.4°
	SC 51	S1	Straw	0.120	0.495	75.8 %	22.6 %	21	1.142 / 0.32	3.36	74.9°
	SC 52	C9	Cotton	0.140	0.410	65.9 %	0.0 %	14	0.834 / 0.23	3.09	73.3°
	SC 53	S3	Straw	0.115	0.455	74.7 %	4.2 %	20	1.076 / 0.30	3.21	71.6°
2011-02-04	SC 54	S4	Straw	0.115	0.460	75.0 %	**17.9 %**	57	1.376 / 0.38	4.30	40.5°
	SC 55	S4	Straw	0.115	0.450	74.4 %	8.0 %	37	1.154 / 0.32	3.55	48.7°

TABLE 10: LIST OF PAPERS DRIED WITH ELECTRIC WATER HEATER (EWH) AND SOLAR COLLECTOR (SC) WITH MISSING DATA POINTS.

Date	Drying #	Paper #	Type of paper	Dry weight (kg)	Wet weight (kg)	Before dry. (%MC,wb)	After dry. (%MC,wb)	Drying time (min)	Energy used for drying (MJ / kWh)	Drying energy [MJ/kg,water]	Average DP temp. (°C)
2011-01-19	EWH 1	CX[r]	Cotton	0.110[s]	0.350	68.6 %	**31.3 %**	26[t]	0.680 / 0.19	3.58	45.1°
	EWH 2	CX[r]	Cotton	0.110[s]	0.365	69.9 %	12.0 %	30[u]	1.122 / 0.31	4.68	55.0°
	EWH 5	C2	Cotton	0.135	0.360[v]	62.5 %	**15.6 %**	18	0.914 / 0.25	4.57	68.5°
	EWH 6	C1	Cotton	0.120	0.365[v]	67.1 %	0.0 %	16	1.041 / 0.29	4.25	67.0°
	EWH 10	TC1[w]	Cotton	0.035	0.125	72.0 %	0.0 %	6	0.429 / 0.12	4.76	68.1°
2011-01-20	EWH 14	TJ1[x]	Jute	0.030	0.090	66.7 %	-20.0 %	6	0.398 / 0.11	6.12	60.9°
	EWH 15	J2[y]	Jute	0.130	0.580	77.6 %	0.0 %	36	1.333 / 0.37	2.96	66.0°
	EWH 21[z]	C3	Cotton	0.115	0.350	67.1 %	4.2 %	18	--[z]	--[z]	66.8°
		C4	Cotton	0.150	0.420	64.3 %	6.3 %	27	--[z]	--[z]	64.9°
2011-01-24	EWH 30	J2	Jute	0.130	0.550	76.4 %	**-4.0 %**	--[aa]	--[aa]	--[aa]	60.0°
2011-01-26	EWH 39	J6	Jute	0.130	0.535	75.7 %	**65.8 %**	30	0.795 / 0.22	5.13	44.7°
	EWH 41	J6	Jute	0.130	0.540	75.9 %	**71.1 %**	13	0.270 / 0.07	3.00	47.8°
2011-02-01	SC 26	C8	Cotton	0.160	0.460	65.2 %	??[bb]	10	1.555 / 0.43	??[bb]	85.2°
	SC 33	C3	Cotton	0.115	0.325	64.6 %	**23.3%**	11	??[cc]	??[cc]	82.0°

[r] The paper CX was used for the first tests and then discarded thus not part of the list of cotton papers C1 to C12.

[s] These values were recorded before a standard for measurement had been developed. Therefore the recorded value of the dry weight was set to the weight after drying from the previous test. The first value recorded was 110 g (with the round up/down method using, i.e. only 5, 10, 15, 20 (g) and so on was recorded due to the high uncertainty in the weighting due to wind affecting the paper sheet during weighting. Doing this measurement in a workshop minimized this but the big door was always open for easy access and some wind could enter that way. This error is though a systematic one that affect all measurements the same way, thus making them at least comparable with each other.

[t] Time with electricity to pump water. Total time from paper on DP until paper off DP = 1h36min.

[u] Time with electricity to pump water. Total time from paper on DP until paper off DP = 41min.

[v] This value was written down halfway through the drying period. The exact value can be off by up to +/- 5 %.

[w] TC1 = Thin Cotton paper 1; Thin papers have not been part of the analysis in this thesis.

[x] TJ1 = Thin Jute paper 1; Thin papers have not been part of the analysis in this thesis.

[y] New program sent to the data logger during this test, 5 min has therefore been created based on the average of the data from the min before and the min after the new program was sent. This to cover the data missing for this time period.

[z] The EWH 21-test consisted of two papers that were dried at the same time; therefore energy used to dry each paper cannot be calculated exactly.

[aa] Paper fell off the DP while no one was present to record the time drying stopped. Also problem with power shortage turning off the pump.

[bb] Data for paperweight after drying is missing.

[cc] Values are negative. Probably due to TCs being wrong. Could have been a tejp or something that didn't work… Vaule with using water temp: 0.701 / 0.19 & 4.00

APPENDIX F: WEIGHT OF PAPERS – FULL LIST

TABLE 11: FULL LIST OF PAPERS USED IN DRYING TESTS. ONLY CONSIST OF TYPE, WEIGHT AND DATE. SOME OF THESE DRYING POINTS HAVE NOT BEEN USED IN FURTHER ANALYSES REGARDING AMOUNT OF ENERGY NEEDED FOR DRYING. THE AIM OF THIS LIST IS TO GIVE AN IDEA OF THE VARIATION IN WEIGHT BETWEEN DIFFERENT PAPER SHEETS.

Type of paper	Paper #	Drying #	Dry weight (kg)	Wet weight (kg)	Weight after drying (kg)	Date
Cotton	CX	EWH 1	0.110	0.350	0.160	2011-01-19
		EWH 2	0.110	0.365	0.125	2011-01-19
		EWH 3	0.110	0.380	0.120	2011-01-19
		EWH 4	0.110	0.355	0.125	2011-01-19
	C1	EWH 6	0.120	0.365	0.120	2011-01-19
		EWH 8	0.120	0.355	0.120	2011-01-19
		EWH 19	0.120	0.380	0.115	2011-01-20
	C2	EWH 5	0.135	0.360	0.160	2011-01-19
		EWH 7	0.135	0.385	0.150	2011-01-19
		EWH 9	0.135	0.390	0.145	2011-01-19
		EWH 18	0.135	0.416	0.135	2011-01-20
	C3	EWH 21	0.115	0.350	0.120	2011-01-20
		SC 20	0.115	0.330	0.115	2011-01-31
		SC 33	0.115	0.325	0.150	2011-02-01
		SC 35	0.115	0.330	0.120	2011-02-01
	C4	EWH 21	0.150	0.420	0.160	2011-01-20
		EWH 45	0.150	0.420	0.145	2011-01-27
		SC 1	0.150	0.415	0.145	2011-01-30
	C5	EWH 22	0.145	0.430	0.170	2011-01-20
	C6	EWH 24	0.130	0.380	0.180	2011-01-23
		EWH 25	0.130	0.385	0.150	2011-01-23
		EWH 26	0.130	0.370	0.135	2011-01-24
		EWH 27	0.130	0.375	0.130	2011-01-24
		EWH 29	0.130	0.390	0.140	2011-01-24
		EWH 31	0.130	0.400	0.135	2011-01-24
		EWH 32	0.130	0.400	0.130	2011-01-24
		EWH 34	0.130	0.400	0.125	2011-01-24
		EWH 37	0.130	0.400	0.130	2011-01-25
		EWH 38	0.130	0.400	0.140	2011-01-26
		SC 19	0.130	0.400	0.130	2011-01-31
		SC 22	0.130	0.410	0.135	2011-01-31
		SC 37	0.130	0.420	0.120	2011-02-01
	C7	SC 30	0.135	0.350	0.130	2011-02-01
	C8	EWH 23	0.160	0.445	0.185	2011-01-20
		SC 3	0.160	0.420	0.180	2011-01-30
		SC 12	0.160	0.435	0.170	2011-01-31
		SC 15	0.160	0.445	0.175	2011-01-31
		SC 26	0.160	0.460	--	2011-02-01
		SC 28	0.160	0.475	0.165	2011-02-01
	C9	EWH 43	0.140	0.380	0.170	2011-01-27
		SC 5	0.140	0.370	0.175	2011-01-31
		SC 7	0.140	0.400	0.145	2011-01-31

		SC 13[q]	0.140	0.390	0.190	2011-01-31
		SC 16	0.140	0.400	0.135	2011-01-31
		SC 18	0.140	0.415	0.140	2011-01-31
		SC 42	0.140	0.400	0.140	2011-02-02
		SC 48	0.140	0.400	0.135	2011-02-03
		SC 52	0.140	0.410	0.140	2011-02-03
	C10		0.155	This paper were never dried		
	C11		0.150	This paper were never dried		
	C12	SC 39	0.140	0.345	0.165	2011-02-02

Type of paper	Paper #	Drying #	Dry weight (kg)	Wet weight (kg)	Weight after drying (kg)	Date
Jute	J1	EWH 11	0.120	0.525	0.125	2011-01-19
		EWH 13	0.120	0.530	0.120	2011-01-19
		EWH 16	0.120	0.540	0.120	2011-01-20
		EWH 20	0.120	0.525	0.140	2011-01-20
		SC 36	0.120	0.525	0.110	2011-02-01
	J2	EWH 12	0.130	0.590	0.120	2011-01-19
		EWH 15	0.130	0.580	0.130	2011-01-20
		EWH 17	0.130	0.545	0.130	2011-01-20
		EWH 28	0.130	0.560	0.140	2011-01-24
		EWH 30	0.130	0.550	0.125	2011-01-24
		EWH 33	0.130	0.560	0.125	2011-01-24
		SC 6	0.130	0.525	0.150	2011-01-31
	J3	SC 9	0.135	0.515	0.165	2011-01-31
		SC 10	0.135	0.585	0.160	2011-01-31
		SC 14	0.135	0.590	0.160	2011-01-31
		SC 17	0.135	0.585	0.155	2011-01-31
		SC 21	0.135	0.580	0.145	2011-01-31
		SC 23	0.135	0.585	0.150	2011-01-31
		SC 24	0.135	0.550	0.135	2011-02-01
		SC 27	0.135	0.575	0.135	2011-02-01
		SC 29	0.135	0.575	0.125	2011-02-01
		SC 31	0.135	0.580	0.140	2011-02-01
		SC 38	0.135	0.580	0.125	2011-02-01
	J4	SC 2	0.155	0.655	0.160	2011-01-30
		SC 4[p]	0.155[dd]	0.650	0.145	2011-01-30
		SC 34	0.150[dd]	0.650	0.150	2011-02-01
	J5		Broke during Beta testing			
	J6	EWH 35	0.130	0.535	0.160	2011-01-25
		EWH 36	0.130	0.535	0.135	2011-01-25
		EWH 39	0.130	0.535	0.380	2011-01-26
		EWH 40	0.130	0.530	0.170	2011-01-26
		EWH 41	0.130	0.540	0.450	2011-01-26
		EWH 42	0.130	0.550	0.155	2011-01-27
		EWH 44	0.130	0.550	0.150	2011-01-27
		SC 8	0.130	0.535	0.160	2011-01-31
		SC 11	0.130	0.540	0.140	2011-01-31
	J7	SC32	0.135	0.555	0.160	2011-02-01
	J8	SC 25	0.135	0.550	0.135	2011-02-01
		SC 43	0.135	0.525	0.170	2011-02-02
		SC 47	0.135	0.515	0.135	2011-02-03
		SC 50	0.135	0.535	0.145	2011-02-03

[dd] 2011:01:30 - A corner broke off. Could still be dried and weighted but reduced the total weight of dry paper to 150 g

	J9	--	0.155	This paper were never dried		
	J10	--	0.145	This paper were never dried		
	J11	SC 40	0.105	0.420	0.095	2011-02-02
	J12	--	0.115	This paper were never dried		

Type of paper	Paper #	Drying #	Dry weight (kg)	Wet weight (kg)	Weight after drying (kg)	Date
Straw	S1	SC 51	0.120	0.495	0.155	2011-02-03
	S2	SC 41	0.120	0.500	0.130	2011-02-02
		SC 44	0.120	0.495	0.110	2011-02-02
	S3	SC 45	0.115	0.460	0.130	2011-02-02
		SC 46	0.115	0.455	0.140	2011-02-03
		SC 49	0.115	0.455	0.140	2011-02-03
		SC 53	0.115	0.455	0.120	2011-02-03
	S4	SC 54	0.115	0.465	0.125	2011-02-03
		SC 55	0.115	0.460	0.140	2011-02-04
		SC 56	0.115	0.450	0.125	2011-02-04