ANNEX 3:

The Technical design of Barbados solar dryer:

MEDIUM SCALE SOLAR CROP DRYERS FOR AGRICULTURAL PRODUCTS

Oliver St C Headley and William Hinds

Centre for Resource Management and Environmental Studies, University of the West Indies, Cave Hill Campus, P.O. Box 64, Bridgetown, Barbados. Telephone 246 417 4316, Fax 246 424 4204,

E-mail oheadley@hotmail.com

Abstract - This paper describes the design and operation of two medium scale solar agricultural dryers, one with a capacity of ten tonnes of hay, the other with a capacity of seven tonnes of onions, and compares them with two other medium scale solar dryers which are used for fruit and timber. Solar dryers of this size need to have mechanically driven fans for air circulation which are powered by mains electricity in all four cases; they are economically viable so long as they do not have to compete with cheap natural gas. In isolated communities, solar energy is quite often the only heat source which can be used to dry low cost agricultural products economically.

1. INTRODUCTION

Solar energy is abundant in the Caribbean islands and Table 1 shows its variation over the year for selected Caribbean territories from Barbados northward. During a typical dry season day, even a small island receives terawatt hours of energy.

Table 1: Solar Radiation is kWh/m^2 at four Caribbean Sites

Place	Position	January	February	March	April	May	June	July	August	September	October	November	December
Adams Airport Barbados	13.0−N, 59.5−W	5.1	5.6	6.0	6.2	6.1	5.9	6.0	6.1	5.7	5.3	5.1	4.8
VC Bird Airport Antigua	17.1−N, 61.8−W	4.55	5.56	5.86	5.86	5.85	5.75	5.90	5.87	5.27	4.95	4.49	4.22
Belize City, Belize	17.5−N, 88.2−W	3.90	4.93	4.46	5.01	4.94	4.83	4.56	5.07	4.79	4.56	4.48	3.92
San Juan, Puerto Rico	18.3−N, 66.0−W	4.32	5.06	5.67	5.89	5.82	5.88	5.99	6.07	5.61	5.05	4.50	4.13

Solar drying is one of the oldest techniques employed in agriculture and solar crop dryers have been built by the Solar Energy Project at the University of the West Indies since 1973, [Headley and Springer (1973), Headley *et al* (1986), Tang Kai *et al* (1993), Balladin *et al* (1997), Balladin and Headley (1999)], and during that time we have dried a wide variety of agricultural crops and timber species such as sorrel (*Hibiscus sabdariffa),* bananas (*Musa sapientum*), yams (*Dioscorea alata),* red cedar (*Cedrela odorata*) and mahogany (*Swietenia macrophylla).* Dryers have varied in size from the 2.2 m^2 wire basket dryer to the 149 m^2 roof collector. Most solar dryers use solar air heaters and the heated air is then passed through the crop. The smaller solar dryers use natural convection or chimneys for air circulation, but for solar collectors of more than 10 m^2, forced convection is usually necessary. Dryers which use an existing building are economically very attractive and Hollick (1998) has described a dryer in India for drying 30 tonnes per day of sesame seeds, chilly and coriander using a collector of 1120 m^2 attached to an existing fossil fueled dryer to replace about 40% of the conventional fuel with solar energy. He calculates a payback time of 2.1 years.

In this paper, we report on two medium scale dryers which were developed for drying onions (*Allium cepa*), hay and similar crops which require a relatively low drying temperature - less than 45−C. We also give a comparison with solar dryers of similar size which are used for other products such as fruit and timber. Dryers tend to be product and site specific and the design is therefore very dependent on what the client wants to dry. In the section below, we give an example of the basic procedure which one follows in the design of a medium scale solar crop dryer.

2. DRYER DESIGN

For a drying temperature of 40 - 45−C, an unglazed collector may be employed since the radiative heat losses to the sky are relatively small at these temperatures. The roof of an existing barn is converted into a solar collector after it is painted flat black and fitted with a ceiling which becomes the duct through which air, the heat transfer fluid, is pumped. The advantage of using the roof of an existing farm building as a solar collector is that, the dryer costs less than if it employs a dedicated collector.

The first dryer which we describe is of this type and uses a corrugated galvanized steel roof of 149 m^2 and a fan which supplies air at 5.66m^3/s with a pressure drop of 747 Pa. Air is sucked into the ceiling space from one end of the roof and is ducted to the fan which then blows it into the plenum chamber at floor level. This dryer is owned and operated by Mr Patrick Bethell of Friendship Plantation in Barbados. Bags of onions or bales of hay are placed on the top of the plenum (which is built on the floor of the barn) whose top is perforated to allow the air to flow through it and then through the crop. The crop is stacked so that heated air does not bypass it and escape to the ambient without removing moisture. This dryer is shown in Figure 1 and does not employ an auxiliary heating system since Bethell did not think it was necessary. Given the airflow rate, psychrometric calculations using the procedure described by Exell (1980) show that drying will take place even when the temperature rise is low. Preliminary calculations assumed that hay was to be dried at 800 bales per week and each bale has a mass of 18.15 kg (40 lbs). After field drying the moisture content of the hay is 40% (wet basis) and this is to be reduced to 15% during drying. The relevant equation to determine the mass M_w of water lost is

Figure 1: The hay dryer at Friendship Plantation, Barbados. The hay has just been dried and reloaded into the trailers on the left; the area on the right where the tractors are parked is the drying bin where the perforated floor is located during a drying run.

$$M_W = M_C [(W_I - W_F)/(100 - W_F)] \quad (1)$$

Where W_I is the initial moisture content
W_F is the final moisture content
and M_C is the initial mass of the crop.

Both W_I and W_F are taken on a wet basis.
M_W is therefore 800 x 18.15 [(40 - 15)/(100 - 15)] = 4270 kg.
If one assumes that each kg of water requires 2.5 MJ of heat for its removal, then the total heat needed is 4270 x 2.5 = 10,676 MJ.
Exell (1980) gives a procedure for calculating the amount of water which can be removed by the airstream, this is then employed using a psychrometric chart. Assuming an input air temperature of 25 C (dry bulb) and a relative humidity of 70%, the psychrometric chart shows that its humidity ratio is 0.0141 kg water/kg dry air. When the solar collector heats it to, say, 40 C (dry bulb), the humidity ratio remains constant. If on passing through the crop, the air absorbs moisture until its relative humidity is 90%, the psychrometric chart shows the humidity ratio to be 0.020 kg water/kg dry air. The change in humidity ratio is therefore 0.020 - 0.0141 = 0.0059 and the corresponding dry bulb temperature is 28.2C. From the gas laws

$$PV = M_A RT \quad (2)$$

Where P is the atmospheric pressure = 101.3 kPa
V is the volume of air in m^3
M_A is the mass of the air in kg
T is the absolute temperature in kelvin, and
R is the gas constant = 0.291 kPa m^3/kg K

For a humidity ratio increase of 0.0059 kg water/kg dry air, each kg of water will require 1/0.0059 = 169.5 kg dry air. For this calculation, the absolute temperature is 28.2 + 273 = 301.2 K and the volume of air needed to remove 1 kg of water is

$$169.5 \times 0.291 \times 301.2/101.3 = 146.6\ m^3;$$

hence 4270 kg will require 4270 x 146.6 = 626,047 m^3. For a drying time of seven days and 8 hours operating time per day, one has 8 x 7 x 3600 = 201,600 seconds. The air flow rate is therefore 626,047/201,600 = 3.1 m^3/s. From previous experience with conventional dryers, it is known that the hay bales in the stack produce a pressure drop of about 3" water gauge = 76.2 mm water gauge = 747 Pa. In a solar air heater system of this type, the frictional losses in the ducts and collector are much smaller than the pressure drop in the bales and can be ignored in the calculation. The fan power requirement P_F is given by the equation

$$P_F = V_A ?P/? \quad (3)$$

Where V_A is the airflow rate in m^3/s, ?P is the pressure drop in Pa and ? is the fan efficiency, taken as 0.7 for this calculation. The fan power requirement is therefore 3.1 x 747/0.7 = 3300 W or 4.4 hp. For extra capacity, we oversized the fan and the one fitted delivers 5.66 m^3/s at a pressure drop of 747 Pa. This dryer's maximum capacity is ten tonnes of hay. The aperture area of the intake to the roof space which is the entry point for air into the solar collector is 12.19 m x 0.102 m = 1.24 m^2. The linear air flow rate is therefore 5.66/1.23 = 4.57 m/s. Determination of the Reynolds number allows us to decide if the flow is turbulent or laminar. The Reynolds number is given by the expression

$$Re = ?V_L D_H/\mu \quad (4)$$

Where D_H is the hydraulic diameter of the duct, = 0.2 m
? is the density of the air = 1.1kg/m^3
V_L is the linear velocity of the air stream = 4.57 m/s
µ is the air's dynamic viscosity = 1.79 x 10^{-5}kg/m.s

$$Re = 1.1 \times 0.2 \times 4.57/1.79 \times 10^{-5} = 56{,}063$$

which means the flow is turbulent which will give good heat transfer. The Nusselt number may be calculated from the Reynolds number by using the equation

$$Nu = 0.0158\ Re^{0.8} \quad (5)$$
$$= 0.0158 \times 56{,}063^{0.8} = 99.45$$

The heat transfer coefficient h_C then be found using the equation

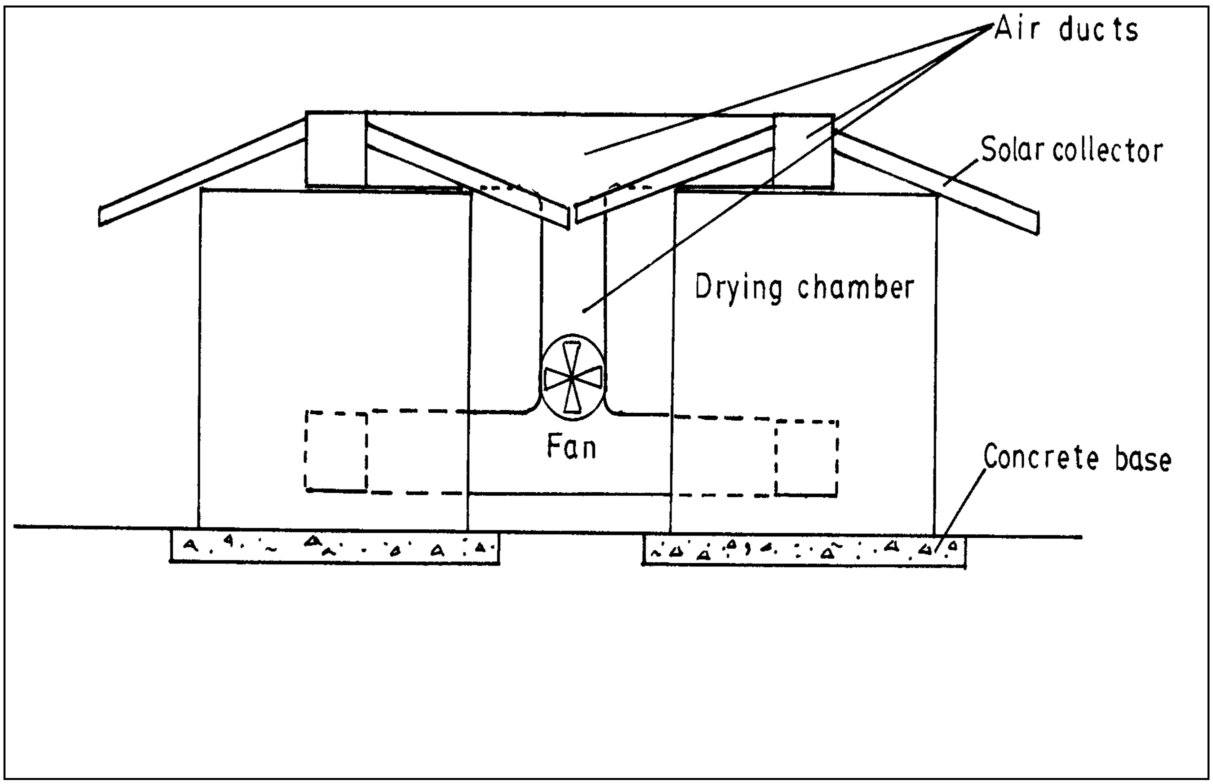
$$h_C = Nu\ k/D_H \quad (6)$$

Where D_H is the hydraulic diameter, and
k is the thermal conductivity of air = 0.029 W/mK Here D_H is twice the plate spacing = 2 x 0.1m = 0.2 m.

$$h_C = 99.45 \times 0.029/0.2 = 14.4\ W/m^2K.$$

The procedure for finding the top loss coefficient and the efficiency factor for the collector follows the method of Duffie and Beckman (1991). The radiative heat transfer coefficient from the plate to the sky was calculated to be 6.39 W/m^2K given a plate temperature of 45?C, a plate emissivity of 0.95 and an ambient temperature of 28?C, assuming that the sky temperature is equal to the ambient temperature. The convective heat transfer coefficient was calculated to be 24.7 W/m^2K, using McAdams equation for a wind velocity of 5 m/s. These combined to give a top loss coefficient U_T of 5.07 W/m^2K. The bottom loss coefficient U_B for the collector was found to be 2.15 W/m^2K given that the duct base was 19mm thick and that its thermal conductivity was 0.041 W/mK. The overall loss coefficient $U_L = U_T + U_B = 7.23$ W/m^2K. The collector efficiency factor F? was calculated to be 0.72, the dimensionless capacitance rate was found to be 9.28, the collector flow factor F? was 0.95 and the collector heat removal factor F_R was 0.68.

Figure 2: Cross section of the solar onion dryer in Antigua



The second dryer, which is situated in Antigua, uses a glazed solar collector array of ~ 40m^2 (20 panels of 1.95 m^2 each) which is connected to a fan by horizontal and vertical ducts. Two horizontal ducts then direct the flow into the drying chambers. By means of the ducting system, the fan sucks air through the solar collectors and forces it into the containers where the onions are placed on racks. One of the containers is insulated and lined with concrete, while the other is simply insulated. The cross section of the air heating space in each solar collector measures 25.4 mm by 914 mm which gives an equivalent diameter of 126 mm for a circular duct. This was the first step in the calculation for determining the pressure drop in the system and the fan power requirement. Standard procedures such as that described by Malik and Buelow (1976) were used for this determination. The fan is 2.2 kW (3 hp) and is rated to deliver 1.16 m^3/s at a pressure drop of 747 Pa (3" water gauge). A linear air flow rate of 1m/s in each collector gives a throughput of 0.92 m^3/s in the complete array of 40 collectors. The procedures described by Duffie and Beckman (1991) were used to determine the collector efficiency factor. The collector was glazed since we needed to raise its efficiency by reducing radiation and convection losses. The two standard 6 metre (20 ft) shipping containers, one of which was modified to enhance heat storage capacity with a lining of concrete blocks for increased thermal mass, formed the drying tunnel. One of the advantages of a drying tunnel is that the product to be dried can be easily loaded unto trolleys and loaded into the dryer. This greatly simplifies materials handling. This dryer is fitted with electrical resistance heaters to supply heat during rainy or cloudy periods and to allow the dryer to be used at night. Even though electricity is 26¢US/kWh in Antigua - which is the second highest electricity tariff in the anglophone Caribbean - the Central Marketing Corporation (CMC) of Antigua preferred to use this heat source since they consider it to be more reliable and less dangerous than liquefied petroleum gas even though the latter is cheaper. The maximum capacity of this dryer is four tonnes of onions and a diagram of it is shown in Figure 2.

3. PERFORMANCE

As can be seen from Table 1, the monthly available solar energy at the V. C. Bird International Airport varies from a high of 5.90 kWh/d in July to a low of 4.22 kWh/d in December. At an efficiency of 40%, the heat output from the collector array is 5.9 x 3.6 x 1.95 x 40 x 0.4 = 663 MJ/d in July. If 2.5 MJ are required to evaporate a kilogram of water, then the solar heat input has a drying capacity of 265 kg of water per day. However the fan delivers air 1.16 m^3/s which amounts to 33,400 m^3 for an eight hour day. The inherent drying capacity of the input air is determined from its temperature and relative humidity, this is calculated using the same procedures that described above for the 149 m^2 dryer. Assuming the same operating conditions as those considered above, where the incoming air is warmed from 25?C to 40?C in the collector, each kg of water requires 146.6 m^3 for its removal. The drying capacity of 33,400 m^3 is therefore 33,400/146.6 = 227.8 kg. It is possible to run a dryer which uses just ambient air and a powerful fan. At the Animal Nutrition Unit in Barbados, an 18.7kW (25 hp) diesel engine was used to power a fan which blew air through a drying bin to dry hay. The fan intake drew air from the engine radiator and from an air-to-air heat exchanger fed by the exhaust gases. Since 70% of the heating value of the fuel is normally lost as waste heat, such a dryer makes excellent use of the energy content of the fuel. The solar dryer built by Soren Sorensen at Stann Creek in Belize is similar in size the Bethell's dryer in Barbados, for a reasonable operating temperature and efficiency, the collector was glazed. In order to improve the availability of the dryer, it was fitted with a wood waste furnace whose flue gases pass through a heat exchanger of old oil drums. This ensures that odours from the burning wood do not ruin the flavour of the drying fruit. This dryer uses a fan of 4.7 m^3/s.

In one run on the Antigua dryer, a tonne of herbs was dried from an initial moisture content of 85% (wet basis) to a final moisture content of 10% (wet basis) in one day. More detailed testing was unfortunately interrupted by the hurricane season and the dryer lost five of its collector panels when Hurricane.

Table 2: Comparison of four medium scale solar dryers

Territory	Antigua	Barbados	Trinidad	Belize
Operator	CMC	Patrick Bethell	David Richardson	Soren Sorensen
Solar collector type	Singly glazed	Bare plate, no glazing	Singly glazed (corrugated plastic)	Singly glazed

Collector area	40 m^2	149 m^2 (1400 sq. ft)	30 m^2	100 m^2
Air circulation system	1 fan, 3 hp (2238 Watts), 1.16 m^3/s	1 fan, 5.66 m^3/s (12,000 cfm)	4 fans, 350W each	1 fan, 4.7 m^3/s (~ 10,000 cfm)
Dryer configuration	Tunnel, two shipping containers	Perforated floor, upward air flow	Two stack, crossflow	Drying tunnel with 12 trolleys
Main products dried	Onions, herbs on occasion	Hay, onions on occasion	Timber	Mango, papaya, banana, pineapple
Load capacity	7 tonnes on trays	350 bales fresh hay (10,000 kg, ~22,000lb)	18 m^3 in two stacks with stickers	4500 kg (10,000 lb) fresh fruit
Drying time	~ 1 week	~ 21 days (3 days at 7 h/d)	3 weeks, two weeks with continuous backup	24 h (mango), 30 h (papaya), 72 h (banana)
Backup heater	Electric resistance	None	Waste wood burner	Waste wood burner with flue gas heat exchanger
Cost, US $	40,000 (1997)	15,000 (1986)	4,200 (1985)	~20,000 (1992)

Georges struck Antigua in September 1998. We have been negotiating with the CMC to determine who will pay for the hurricane damage, this has yet to be resolved. Table 2 compares the Antigua dryer with three other medium scale dryers in the Caribbean. These dryers are all designed to dry loads of several tonnes of agricultural products. Many agricultural products are currently dried using fossil fuels. In Trinidad, a large copra dryer on a coconut estate dries 9100 kg of copra in 34 hours using diesel fuel for heating and a 10 hp fan for air circulation. During this time, it consumes 660 litres of diesel fuel at a cost of $145 US and $9.30 US of electricity (254 kWh at 3.67¢ US/kWh). Since the fuel cost is much greater than the electricity cost, it clearly pays to reduce the fuel cost by having a solar collector mounted on the roof of the drying barn and using it to supply hot air to the dryer. The payback period for this modification will be examined under the section on economic considerations.

4. ECONOMIC CONSIDERATIONS

In Barbados, the cheapest of the fossil fuels is natural gas. For a small consumer, the price varies with the amount consumed according to the figures given in Table 3. Assuming a heating value of 40MJ/m^3 and a burner efficiency of 75%, one can calculate the annual cost of the solar heat which is produced by the solar collector at Friendship Plantation. If the collector is assumed to have an average efficiency of 40% over the year, noting from Table 1 that the average annual insolation in Barbados is 5.33 kWh/m^2d; assuming 300 days of operation per year, then from a surface area of 149 m^2 it should deliver 5.33 x 0.4 x 149 x 300 x 3.6 MJ = 343,081 MJ.

Table 3: Natural Gas Price for a Small Consumer

Natural Gas Consumed (m^3)	Price (US$)
The first 150	0.65
The next 2250	0.60
The next 5300	0.58
The next 8700	0.57

Assuming a heating value of 40MJ/m^3 and a burner efficiency of 75%, one can calculate the annual cost of the solar heat which is produced by the solar collector. If the collector is assumed to have an average efficiency of 40% over the year, noting from Table 1 that the average annual insolation in Barbados is 5.33 kWh/m^2d; assuming 300 days of operation per year, then from a surface area of 149 m^2 it should deliver 5.33 x 0.4 x 149 x 300 x 3.6 MJ = 343,081 MJ. In terms of natural gas heating delivered from the burner, this would be 343,081/(40 x 0.75) = 11,400m^3. From the prices given in Table 3, this cost comes to $6630.50 US With a dryer cost of $15,000 US, the repayment period based on replacing fuel with the solar energy collected is 15,000/6630.5 = 2.26 years. Hence at Barbadian prices, solar energy for this dryer is competitive with natural gas. At the Trinidadian price of $1US per million Btu (1055.1 MJ), assuming a burner efficiency of 75%, a year's energy output from the solar collector is worth 343,081/(1055.1 x 0.75) = $433.57 US. The payback time with Trinidadian natural gas as fuel is therefore 15,000/433.57 = 35.6 years. Clearly solar drying cannot compete with natural gas where the latter is cheap.

5. CONCLUSIONS

Solar crop dryers are a cost effective solution to some of the problems of food preservation in sunny climates. In places where fossil fuel is cheap and readily available, such as natural gas in Barbados and Trinidad & Tobago, the decision to use solar dryers may be based on purely environmental considerations, since the economics of the dryer do not allow it to compete with cheap natural gas produced as associated gas as a by product of crude oil production. The solar dryer with the least initial capital cost is one which uses an existing farm building or adds a solar air heater to an existing conventional crop dryer. While multi-crop dryers may seem to be an ideal solution, the fact is that most operators prefer to have a dryer which is dedicated to one or two crops or to a specific kind of crop, fruit for example, since the compromises inherent in a multi-purpose dryer often result in reduced efficiency for its primary product.

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