421-644: Research Project

Technical and Financial Feasibility of a Solar Dryer in Bhutan

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ABSTRACT

The technical and financial performance of an existing solar crop dryer at Khao-kor, Thailand has been evaluated for possible replication in Bhutan. The complete dryer system has been modelled using TRNSYS and the collector area was optimised to give minimum drying cost. From the evaluation, the average collector, pick-up and system efficiencies were found as 44%, 23% and 18% respectively. The solar contribution to the load is 33% when the dryer is used for 304 days in a year. Chilli and beef were selected as products to be dried as they are an integral part of Bhutan's dishes. The drying cost is US \$ 7.94 and 5.96 per kg of dry matter for chilli and beef respectively using the solar dryer system. The corresponding costs using an electric heating system is US \$ 7.76 and 6.25 per kg of dry matter for chilli and beef respectively. The solar dryer system was found to be cheaper compared to an electric heating system, however, from the commercial point of view, without any incentives, both the systems are financially non-viable in Bhutan. Nevertheless, the solar dryer system is more attractive than the electric heating system as its NPV at 13% real discount rate is higher.

DECLARATION

To the best of my knowledge and belief, this report neither contains material which has been accepted for the award of any other degree in any university nor any material previously published or written by another person, except where due reference is made in text. The length of this report exclusive of tables, figures, references and appendices is approximately 15000 words.

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ACRONYMS

AIT	: Asian Institute of Technology	kW	: Kilo Watt
AVG	: Average Day Model	kWh	: Kilo Watt hour
BCR	: Benefit-Cost Ratio	LTD	: Long-term data
BPC	: Bhutan Power Corporation	m	: Metre
BSR	: Bhutan Schedule of Rates	mm	: Millimetre
CGI	: Corrugated iron	MoA	: Ministry of Agriculture
COM	: Compressed Weather Generation	MJ	: Mega Joules
cm	: Centimetre	MWh	: Mega Watt hour
CSO	: Central Statistical Organisation of Bhutan	N	: North
db	: Dry basis	NASA	: National Aeronautics and Space Administration
EIU	: Economist Intelligence Unit	NPV	: Net Present Value
EMC	: Equilibrium Moisture Content	Nu	: Ngultrum (Bhutan's local currency, US \$ 1 $\equiv$ Nu 45)
FAO	: Food and Agriculture Organisation	PCS	: Planning Commission Secretariat of Bhutan
GDP	: Gross Domestic Product	pJ	: Peta Joules
GEN	: Hourly Weather Generator	RMA	: Royal Monetary Authority of Bhutan
GI	: Galvanised iron	RMS	: Root Mean Square
GJ	: Giga Joules	RMSD	: Root Mean Square Deviation
gm	: Gram	s	: Second
Hz	: Hertz	S	: South
ITDG	: Intermediate Technology Development Group	SQCD	: Standard and Quality Control Division of Bhutan
IEA	: International Energy Agency	TMY	: Typical Meteorological Year
IRR	: Internal Rate of Return	TRY	: Test Reference Year
kg	: Kilogram	USDA	: United States Department of Agriculture
kJ	: Kilo Joules	V	: Voltage
		wb	: Wet basis

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1. INTRODUCTION

1.1 Drying of crops

The seasonal characteristic of crops makes preservation necessary to assure a regular and continuous supply to the consumers through the year. Drying is one of the oldest and most practical methods of food preservation. Sun drying of agricultural produce has been practiced as a preservation technique in various parts of the world (Desrosier 1970; Ekechukwu & Norton 1999; Esper & Muhlbauer 1998; Farkas & Smith 1987; Gallali *et al.* 2000; Gupta *et al.* 2002; ITDG 2004; Jayaraman & Das Gupta 1987; Kaensup *et al.* 2002; Lutz *et al.* 1987; Pangavhane & Sawhney 2002; Sarkar & Saleh 2002; Sharma *et al.* 1986).

Most developing countries use the traditional sun drying method of spreading the agricultural produce on flat open ground with the produce directly exposed to the sun. The traditional sun drying method is associated with drawbacks like the requirement of large spaces and a long drying time, contamination of crops from foreign materials, crops subjected to insect infestation and crops being susceptible to re-absorption of moisture (Bassey 1981; Clark 1981; Ekechukwu & Norton 1999; El-Sebaai *et al.* 2002; Exell & Kornsakoo 1978; Fuller 1998; Lutz *et al.* 1987; Madhlopa *et al.* 2002; Maroulis & Saravacos 1986; Sarkar & Saleh 2002; Tiris *et al.* 1995; Vlachos *et al.* 2002). Moreover, traditional sun drying does not produce uniform quality (Keddie 1981). Also the traditional sun drying method is weather dependent and there is no shelter to protect the agricultural produce in the event of rain. As a result new drying methods are being implemented.

Most of the commercial crop dryers use fossil fuel. Wood and conventional fossil fuels are being used extensively for crop drying in most countries. Apart from this, expensive fuels like diesel and propane are also being used for crop drying (IEA 2003). Because of the increase in fuel consumption with a subsequent increase in price of conventional fossil fuels, solar dryers are being studied widely to substitute for the conventional method of crop drying (Pangavhane & Sawhney 2002). Solar dryers are an appropriate preservation technology for a sustainable world and are being used in

both developed and developing countries. A study done by IEA in 1999 estimated that solar drying of crops could save 657 to 1530 PJ of energy annually (IEA 2003). This is more applicable but not limited to crops that are dried at temperature less than 60° C. For crops that are dried at temperatures higher than 60°C, solar drying could be used as a supplemental system.

1.2 Crop drying in Bhutan

Agriculture forms the backbone of the Bhutan's economy contributing 32.4% of estimated GDP in 2002 (CSO 2003; EIU 2004) (see Appendix 1 for short introduction on Bhutan). Chilli is the most important spice crop, for both sale and consumption. In Bhutan, both green (fresh) and dried chilli is consumed like other vegetables and commonly known as a vegetable rather than as a spice (Berke 2002; Wissink 2004). Also chilli is not only an important part of family diets but one of the main cash crops. It is reported that farmers of the main chilli growing regions earn US \$ 555 to US \$ 667 per annum from the sale of chilli (Wangchuk 2004). In 2000, nearly 3000 tones of chilli were produced and about 1000 tonnes were traded (MoA 2000) (see Appendix 2 for details). The common species is *Capsicum annum* L which is large, fleshy and mild (Luitel 2004).

Among other vegetables, chilli has captured the Bhutanese market both in the rural community and the urban areas. Depending upon location and climate, chilli is grown in different seasons. Although chilli is grown all over Bhutan, major production is concentrated in the districts of Paro, Punakha and Wangdue in the west and Trashiyangtse and Trashigang in the east (MoA 2000). Fig.1.1 shows the chilli growing regions in Bhutan. However, regions in higher altitudes grow chilli from the months of April-May and harvest in the months of August-September while in lower regions it is grown in Feb-March and harvested in the months of April-May. While the lower regions do not face any problem in marketing chilli, the upper region faces a problem of marketing as chilli is harvested in the months of August-September when it is harvested all over Bhutan. The problem is further compounded by the rainy season which falls at the same time as the chilli harvesting time (Luitel 2004).

Fig. 1.1. Map of Bhutan (1-5 shows main chilli growing districts)

Similarly, meat also forms an indispensable part of the Bhutanese cuisine. Although, both fresh and dried meats are consumed like vegetables, Bhutanese prefer dried meat to fresh meat. In 2002, residents of Bhutan's capital Thimphu consumed 1438 tonnes of meat valued at US \$ 3 million, of which 665 tonnes was beef valued at US \$ one million (Dorji 2004). The rest was pork, chicken, mutton and fish. However, due to religious sentiments, slaughtering of animals is limited, so a substantial quantity of meat has to be imported from India (Wissink 2004).

1.3 Problem statement

As the chilli harvest season coincides with the monsoon, it is not always possible to dry chilli. Thus, it has become a common feature in Bhutan to see chilli flooding the local market for a relatively short period and then disappearing until the next season. This leads to very low financial incentives for farmers. This may be reduced if chilli could be dried when it is available abundantly. The dried product can be sold during

the off-season to earn more. Although, chilli is being dried by the farmers, the method used for drying is very crude.

Fig. 1.2 illustrates the present chilli drying method in Bhutan. Chilli is dried on open ground with no shelter. It is common to see roof tops covered with chilli during the summer months. This results in poor quality associated with huge financial loss to the poor farmers. Chilli is also being dried by tying in strings and hanging on the walls. At present, no study has been done to estimate the loss of chilli from drying in this way and no alternative options have been investigated to improve the drying technique. Thus, it is envisaged that improvement in drying techniques may result in a better quality of dried chilli and fetch better prices for the farmers.

Fig. 1.2. Chilli drying in Bhutan

Likewise, the beef drying method is also very crude. Fig. 1.3 shows the beef drying method in Bhutan. The beef is subjected to insect infestation as well as being exposed to rain. It is very common to see every household drying beef in the open air. The quality of dried beef is very poor, resulting in loss of beef. An improved way of drying may result in better quality and minimise losses.

Considering the importance of chilli and meat in Bhutan and need to dry them when they are available abundantly, there is a need to study improved drying systems which are reliable and affordable to the farmers of Bhutan. However, Bhutan, situated in the Himalayas has no proven deposits of crude oil and natural gas (PCS 1997, 2002), so use of conventional drying systems would be too expensive for the Bhutanese farmers.

Thus, an alternative approach, as suggested by the literature, is to use solar crop dryers. This technique has been used in both developed and developing countries with some success.

Fig. 1.3. Beef drying in Bhutan

Therefore, this study focuses on performance evaluation of an existing solar dryer in Thailand for possible replication in Bhutan. The principle product for investigation is chilli and beef is a supplemental product to be dried. The mode of study will be based on simulation, using a simulation software TRNSYS and determining the design parameters and performance of the dryer.

1.4 Aim, objectives and scope of work

1.4.1 Aim

The aim of this study is to evaluate the performance of an existing solar dryer system at Khao-kor in Thailand for possible adaptation in Bhutan.

1.4.2 Objectives

The objectives of this study are:

- To investigate present system of chilli and beef drying in Bhutan
- To generate a Typical Meteorological Year data file for Bhutan

- Evaluate the existing Khao-kor solar dryer system with respect to technical performance and financial viability in Bhutan
- Propose an appropriate model and design parameters for a solar dryer for Bhutan
- Estimate financial benefits from the solar drying system

1.4.3 Scope of work

The study is limited to the following:

- The performance evaluation is limited to drying of chilli; and beef is investigated as a supplemental product to be dried when there are no chillies to dry.
- Study was done for Paro region of Bhutan and thus performance may vary for other regions.
- Financial feasibility is true only for Paro, and for other regions, the results may vary.
- The study was based on the TMY data generated using Type 54 weather generator with inputs obtained from NASA satellite which has a RMS bias of up to $\pm 17\%$ and thus the results may vary from practical investigations.

1.4 Structure of the report

The report comprises seven sections. Section One is the introduction; the second and third sections present a review of drying principles and solar dryers with an emphasis on chilli and meat dryers. The fourth section describes the generation of the TMY data for Bhutan. The fifth and sixth sections present the evaluation of the technical and financial performance of the existing dryer in Thailand and the necessary modification required for possible replication in Bhutan. The last section presents the conclusions and recommendations on the performance evaluation. The last section also looks at the areas that require further analysis.

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2. CROP DRYING FUNDAMENTALS

2.1 Introduction

Most agricultural crops have high moisture content during the time of harvest. Such crops deteriorate due to growth of mould, fungi, bacteria etc. (Ali & Sakr 1981; Jayaraman & Das Gupta 1987; Tayeb 1986). The basic principle of drying is to reduce the moisture content of the crops to a level that prevents deterioration within a certain period of time and to reduce the weight and volume of crops for cheaper storage and transport. Drying is a dual process of heat transfer from air to crops and mass transfer from crops to air (Midilli & Kucuk 2003a). In this process moisture is extracted from the crops by heating and the released water vapour is carried away by the air mass flowing around it.

2.2 Drying process

When a product at constant moisture content is heated, the vapour pressure increases and results in movement of moisture from the product to its environment which is at a lower vapour pressure. The process consists of two periods; the constant drying rate and the falling drying rate (Ali & Sakr 1981; Andales 1981; Carpio 1981; Fuller 1998; Hall 1957; Imre 1987; Midilli & Kucuk 2003b; Suzuki *et al.* 1977). Fig. 2.1 illustrates the drying process.

Fig. 2.1. Illustration of drying process

2.2.1 Constant rate period

During this period, drying takes place from the surface of the product and the wet surface of the product behaves like a free water surface (Ali & Sakr 1981; Hall 1957). For the constant rate drying process to continue, the moisture evaporated from the product's surface should be equal to the moisture supplied to the surface. In this case the drying rate is dependent on the area of product exposed to drying air, the vapour pressure difference between the drying air and product, the coefficient of mass transfer and the velocity of drying air (Ekechukwu 1999; Hall 1957, 1980). Drying of products like sand, stone, paper, washed seed and grain takes place in the constant rate period (Ekechukwu 1999; Hall 1957, 1980). The constant rate drying period is short for farm crops. Studies by Hossian and Bala (2002), and Gupta *et al.* (2002) found that chilli does not exhibit a constant rate drying period. All the drying occurs within the falling rate period. Thus, the constant rate is not pursued further in this study.

2.2.2 Falling rate period

The falling rate period occurs after the constant rate period. The critical moisture content is between the constant and falling rate periods (point C in Fig. 2.1). In this case the drying rate is controlled by the movement of moisture from within the products to the surface by diffusion and removal of water from the surface. As the area of wet surface decreases, the rate of diffusion decreases and hence the drying rate. After some time, a point is reached where water can no longer diffuse to the surface as rapidly as it is evaporated and thus reaches an equilibrium moisture content.

In grain and forage, the critical moisture content is less than the initial moisture content, thus the drying takes place in the falling rate period (Hall 1957, 1980). However, for fruits and vegetables the initial moisture content is higher than the critical moisture content and thus drying occurs in both the constant and falling rate periods (Ekechukwu 1999). Even when the constant rate period exists, it is often neglected by the researchers owing to its very short period and the very small amount of water to be removed (Hall 1957, 1980).

2.3 Drying classification

Drying of crops can be classified into two categories based on the thickness of the crop bed (Anwar & Tiwari 2001; Ekechukwu 1999; Hall 1957). Drying bed thicknesses up to 20 cm are classified as thin bed drying while for more than 20 cm, it is classified as deep bed drying (Anwar & Tiwari 2001). Fig. 2.2 illustrates thin and deep layer drying.

2.3.1 Thin layer drying

In this case the crop is entirely exposed to the drying air flowing through it. The drying rate is dependent on the crop type, size and moisture content of crop and the drying temperature (Ekechukwu 1999; Hall 1957). Drying rate for thin bed drying during the falling rate period is based on Newton's law of cooling which states that "the rate of change in temperature of a body surrounded by a medium at constant temperature is proportional to the difference in temperature between the body and surrounding medium when the temperature difference is small" (Equation 2.1) (Hall 1957, 1980).

Fig. 2.2. Thin and deep layer drying

$$\frac{d\theta}{dt} = -k \times (\theta - \theta_e) \quad (2.1)$$

Where k = heating constant

θ = temperature at time t

θ_e = Surrounding medium temperature ($^{\circ}\text{K}$)

By re-arranging and integrating Equation 2.1, an exponential equation is obtained as shown in Equation 2.2,

$$\frac{\theta - \theta_e}{\theta_o - \theta_e} = e^{-kt} \quad (2.2)$$

By substituting temperature θ by moisture content on dry basis, Equation 2.3 is obtained.

$$\frac{M - M_e}{M_o - M_e} = e^{-kt} \quad (2.3)$$

Here M is the moisture content (db) at any time t , M_e is the equilibrium moisture content, M_o is the initial moisture content (db) and k is the drying constant.

2.3.2 Deep layer drying

In this case, drying of crops can be considered as several thin layers in which the humidity and temperature of air entering and leaving each layer varies with time depending on stage of drying. The main drying takes place in the drying zone which moves in the direction of air flow as shown in Fig 2.2. As the drying air flows, the crop layer where air enters dries faster than the upper layer and thus reaches a low moisture content level by the time the upper most layer reaches its equilibrium moisture content (Ekechukwu 1999; Hall 1957). The moisture content difference between the top and the bottom layer depends on the air flow. A higher air flow is associated with a lesser difference in moisture content.

2.4 Drying parameters

The rate of drying is affected by the properties of the drying air i.e. temperature, velocity of air flow and humidity. Ateba and Mittal (1994) considered most crops as porous and capillary material and thus the structure of the crop determines the rate of

moisture migration from the inner layer to the surface of the crop. Also the method of preparation prior to drying, and shape and size of the piece affects the drying rate.

2.4.1 Temperature

The drying temperature differs with the type of food being dried. In general, the rate of drying increases with an increase in drying temperature (Lahsasni *et al.* 2004). Higher temperature also destroys bacteria, enzymes, fungi, eggs and larvae. However, there are some problems associated with higher temperatures. If the temperature of dryer air is high and humidity is low, then surface moisture will be removed faster than the interior moisture can move to the surface. This can harden the surface and retard the flow of interior moisture to the surface thus prohibiting the drying of the inner layer (Vlachos *et al.* 2002). This is further confirmed by Ali and Sakr's (1981) investigation of drying Jew's mallow and okra. They found that if the drying temperature and velocity of drying air are high, then the outer layer dries faster than the inner layers and, after being removed from the dryer, the surface becomes moist again due to re-absorption of moisture. Because of this Bansal and Misra (1987) recommended levels of temperature for each type of food products (Table 2.1).

Table 2.1. Recommended temperature for drying

Product	Moisture content		Maximum temperature allowable for drying (° C)
	Initial (%)	Final (%)	
Bananas	80	15	70
Cabbage	80	4	55
Carrots	70	5	75
Cauliflower	80	6	65
Chilli	80	5	65
Garlic	80	4	55
Green beans	70	5	75
Green peas	80	5	65
Onions	80	4	55
Potatoes	75	13	75
Sweet potato	75	7	75

Source: (Bansal & Misra 1987)

Warm air can hold more moisture than cold air, so the amount required depends on the temperature and absolute humidity when it enters the dryer. Table 2.2 shows the absorption capacity of air at different temperatures and relative humidities

Table 2.2. Moisture absorption capacity (gm of water/m³ of air)

Initial relative humidity (%)	Not heated (20°C)	Heated to 40°C	Heated to 60°C
40	4.3	9.2	16.3
60	1.4	8.2	15.6
80	0.0	7.1	14.9

Source: (ITDG 2004a)

2.4.2 Air flow

At constant drying air temperature, the drying time decreases with an increase in air flow. The increase in velocity and volume of air flow results in a decrease in dryer temperature. A higher velocity means more air is available per unit time, so more heat and thus more water can be carried away in a given time. The rate of evaporation also depends on surface area and porosity of the particle. At constant air flow, the drying time decreases as the drying temperature increases and vice versa.

2.4.3 Relative humidity

The level of relative humidity also affects the drying time. Higher relative humidity is associated with less capacity to hold moisture, thus longer drying time. Also at higher humidity, more air will be required with a higher air temperature.

2.5 Moisture content

The percentage moisture content of crops can be expressed in two different ways (Exell 1980; Sharma *et al.* 1986):

- Wet basis – It is the ratio of weight of water to the total weight of dry matter plus water (Equation 2.4).

$$MC_{(wb)} = \frac{100 \times (W - W_d)}{W} \quad (2.4)$$

- Dry basis – It is the ratio of weight of water to the dry matter weight (Equation 2.5).

$$MC_{(db)} = \frac{100 \times (W - W_d)}{W_d} \quad (2.5)$$

Where $MC_{(wb)}$ = Moisture content on wet basis
 $MC_{(db)}$ = Moisture content on dry basis
 W = Weight of wet sample
 W_d = Weight of dry matter

The two moisture contents are inter-related by the Equations 2.6 and 2.7

$$MC_{(wb)} = 1 - \left[\frac{1}{MC_{(db)} + 1} \right] \quad (2.6)$$

$$MC_{(db)} = \left[\frac{1}{(1 - MC_{(wb)})} \right] - 1 \quad (2.7)$$

The dry basis moisture content is used for engineering calculations and research since the base of the ratio is constant with varying percentage moisture content (Bala 1997; Ekechukwu 1999; Hall 1980). Thus, in this study dry basis moisture content was used for calculations.

2.5.1 *Equilibrium moisture content*

Ambient air consists of dry air and water vapour. However, the ratio of water vapour to dry air is very small. The moisture content of the crops exposed to ambient air varies with respect to relative humidity. The greater the relative humidity, the greater uptake of moisture and vice versa. Although the uptake is slow, after some time a new value of moisture content is reached. Table 2.3 shows the equilibrium moisture content of different crops at various relative humidities.

Table 2.3. Equilibrium moisture content

Crops	Air Relative humidity (%)						
	40	50	60	70	75	80	90
Wheat	10.7	12.0	13.7	15.6	16.6	17.6	23.0
Maize	11.0	12.0	13.0	15.0	15.5	16.0	20.0
Rye	10.0	11.6	13.2	14.8	16.1	17.3	24.6
Peas	9.4	11.1	13.1	15.5	17.2	19.5	27.7
Beans	9.1	11.1	13.1	15.8	18.0	20.4	28.0
Grass	8.9	10.3	11.6	13.9	15.4	17.4	23.3
Onions	8.3	9.6	10.8	12.6	14.1	16.2	23.5

Source: (FAO 1985)

The equilibrium moisture content (EMC) is dependent on the relative humidity and temperature of environment, and also on species, variety and maturity of the crop. It indicates whether the crop will absorb or lose moisture at a given temperature and relative humidity (Charm 1978). At the EMC, the rate of moisture loss from the crop is equal to the rate of moisture gain of the crop from the atmosphere (Hall 1980). EMC could be classified into two types i.e. static and dynamic equilibrium moisture content (Bala 1997). Static EMC is obtained after prolonged exposure of the crop to the atmosphere while the dynamic EMC is obtained by fitting the thin layer drying equation to experimental data (Bala 1997). Ward *et al.* (1954 in Bala 1997) recommended that static and dynamic EMC should be used for storage and drying respectively.

The relationship between EMC and relative humidity at a constant temperature is illustrated by a curve called an isotherm. Fig. 2.3 shows a typical isotherm curves for an agricultural crop. An adsorption isotherm indicates moisture content versus relative humidity of the crop subjected to absorption of moisture while a desorption isotherm indicates a drying phenomenon.

Fig. 2.3. Adsorption and desorption isotherms

2.6 Properties of chilli and beef

2.6.1 Chilli

Sitthiphong *et al.* (1989) investigated the physical properties of the green chillies in Thailand. The diameter and length of chillies were recorded as 10 to 15 mm and 100 to 200 mm respectively, while Kalemullah and Kailappan (2003) found that since the cylindricity value (86.9%) was more than the sphericity value (60.9%), chillies can thus be considered to be cylindrical. The bulk density of wet chilli at 83% moisture content was 325 kg/m³ while dry chilli at 13% moisture content was 80 kg/m³ (Sitthiphong *et al.* 1989). The green chillies were found to bleach when exposed to temperature above 45°C, red chillies do not bleach regardless of drying temperature (Reilly 1996). This was explained by Reilly (1996) to be due to the presence of colour pigment anthocyanin in red chillies, which is less sensitive to damage by light compared to the chlorophyll present in green chillies, which is highly sensitive to damage by light and heat. As only red chillies are dried in Bhutan, the problem of bleaching does not arise.

Pruthi (1993) and Miaruddin *et al.* (1995 in Hossian & Bala 2002) reported a moisture content of 70 to 80% during the time of harvest and recommended a final moisture

content of 8 to 10% for storage and 4 to 5% for grinding purposes. Also Bansal and Misra (1987) found the moisture content of fresh chilli to be 80% while Kaleemullah and Kailappan (2003) report a moisture content of 75 to 80% at full maturity. Bosland and Votava (2003) recommended a final moisture content of 8 to 11% for safe storage. Dogantan *et al.* (1987) noted an initial moisture content of 80% and 10% for storage. However, if too much moisture is removed, then the colour may fade rapidly but on the other hand, mould may grow if the moisture content is high. Table 2.4 summarises the parameters of the chilli used in this study based on the literature.

Table 2.4: Parameters of chilli used in this study

Parameters	Value	Unit
Initial moisture content	567	%
Final moisture content	10	%
Bulk density (fresh)	325	kg/m ³
Length	100 - 200	mm
Diameter	10 - 15	mm

2.6.2 Meat (beef)

Traditionally, meat is dried by slicing into strips and hanging over ropes or wires without any cover. There is no standard length or thickness for the strips. FAO (1990) recommended that the length of the strips be 20 to 70 cm, however, in Bhutan the longer strips are considered better to prepare traditional meals. Before slicing the meat, it is de-boned and separated from tissues, however, fats are not removed for drying. Normally, it takes 5 to 7 days to dry beef by the natural sun drying method. The meat is dried until the strips break off when bent. The moisture content of fresh beef was estimated as 70% (wb) by ITDG (2004b) while Holley (1985) considered it to be 68% (wb). Further Lisse and Wack (1998) reported the moisture content of beef strips as $80 \pm 1.1\%$ (wb). Fuller and Lu Aye (2002) considered the initial moisture content of beef as 80%. In this study, an initial moisture content of 80% will be assumed equal to the values assumed by Lisse and Wack (1998) and Fuller and Lu Aye (2002).

2.7 Methods of drying

In general, crop dryers can be grouped into two groups: Traditional sun drying and conventional drying methods. As reported in Section 1.1, traditional sun drying is a slow process and losses may reach 30 to 40% in tropical countries (Costa *et al.* 2003) and require approximately one acre of drying surface per 20 acres of crop land (Desrosier 1970 pp 124). While conventional dryers have high efficiency and produce a uniform high quality product, they are expensive, and so not affordable by rural farmers (Ivanova & Andonov 2001). Lutz *et al.* (1987) reported that even the smallest and most simple oil or gas fired conventional dryers could not be applied in small scale firms. Thus, an alternative approach is to use a solar dryer which uses free solar energy available from the sun's radiation. Most agricultural products are harvested during the summer months when solar radiation is high (Maroulis & Saravacos 1986). This increases the opportunity to use solar energy for crop drying. The next section describes solar dryers in detail.

2.8 Conclusions

The drying processes of any products have been explained in the preceding sections. Drying process can be summarised as evaporation of the water content of product from the surface to the surrounding medium and movement of water from inside the product to the surface by means of diffusion. Drying needs heat to evaporate water from the product and a medium to carry away water from the surface. Air is used both as a medium to transfer heat to the product as well as to carry away the water from the surface. However, air has to be heated to a certain level of temperature based on a safe drying temperature to increase the moisture absorption capacity. This requires an external energy source which makes mechanical dryers expensive in developing countries. Thus solar dryers are preferred as abundant and free solar energy is available from the sun's radiation.

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3. SOLAR DRYERS

3.1 Introduction

Solar drying is a method of sun drying (ITDG 2004). A solar crop dryer can reduce spoilage, waste, insect infestation, attack by rodents and birds compared to the traditional method of drying. Solar drying of crops also improves the quality of produce considerably (Bansal & Misra 1987; Farkas & Smith 1987; Lahsasni *et al.* 2004; Lutz *et al.* 1987). Several studies in different countries indicate that solar dryers can be effectively used for drying crops and it is a question of designing the right type of solar dryer (Esper & Muhlbauer 1998; Gallali *et al.* 2000; Pangavhane & Sawhney 2002).

3.2 Types of solar dryers

Ekechukwu and Norton (1999a) and Leon *et al.* (2002) classified solar dryers into two groups: active dryers and passive dryers. Both types were further classified into three types of integral, distributed and mixed mode solar dryers.

3.2.1 Active and Passive solar dryers

Active and passive solar dryers are differentiated, based on the method of air convection inside the dryer. Active solar dryers use a fan to circulate the air while passive solar dryers do not require an external fan. The warm air inside the dryer is lighter than the cooler air outside. The difference in density creates a pressure difference which forces the air through the dryer. Thus, active and passive solar dryers are also commonly known as forced and natural convection solar dryers respectively.

In general, natural convection solar dryers are preferred by the farmers due to the relatively simple construction, operation and low cost (Soponronnarit 1995). However Ekechukwu and Norton (1998) noted that natural convection solar dryers are highly dependent on weather conditions. For example, the performance of a solar dryer was

better during dry summer months, requiring two days less than in winter to dry the same quantity of cassava chips.

3.2.2 *Integral and distributed solar dryers*

Integral and distributed solar dryers are differentiated by the mode of utilising solar radiation (Vlachos *et al.* 2002). In the case of integral solar dryers, the collector is an integral part of the drying unit. In this type, the crop absorbs the solar radiation directly. Direct solar dryers are simple to operate but it is difficult to control the temperature.

Unlike integral solar dryers, distributed solar dryers consist of separate units of solar collector and dryer. In this type, the crop is not exposed to direct radiation but is heated by convection by the heated air. Thus, integral and distributed solar dryers are also commonly known as direct and indirect solar dryers respectively.

3.3 Solar air collectors

Collectors are devices employed to absorb useful energy from incident solar radiation. Solar collectors are of two types: concentrating and flat plate (Ekechukwu & Norton 1999b). Concentrating collectors operate at higher temperatures than flat plate collectors. Furthermore Ekechukwu and Norton (1999b) classified flat plate collectors into two groups: bare plate and covered plate, while Soponronnarit (1995) classified collectors into three types: flat plate, non-flat plate and integrated collector storage. For solar crop dryers, flat plate collectors are more appropriate as they are simple, economical and provide the desired temperatures (Ekechukwu & Norton 1999b; Soponronnarit 1995). Thus only flat plate solar collectors are dealt with in detail in this report.

Flat plate solar collectors are further classified into bare flat plate, covered flat plate and covered flat plate with a still air gap. Fig. 3.1 shows three types of flat plate solar collectors.

Fig. 3.1. Flat plate solar collector

Source: (Soponronnarit 1995)

Bare flat plate collectors are the simplest form of solar collectors. These consist of an air duct with an insulated rear surface. The upper surface acts as a solar energy absorber. These collectors are associated with high thermal losses due to their exposed surfaces and thus have lower thermal efficiency. Bare flat plate solar collectors are suitable for low temperature solar drying and are widely used in both natural and forced convection solar dryer systems due to their low cost of construction.

Similarly, covered flat plate collectors also consist of an air duct with an insulated rear surface but the upper surface is covered with either glass or polyethylene sheet. Although the transmission of incoming solar radiation is reduced by about 10%, the thermal efficiency is higher compared to bare flat plate solar collectors due to minimised radiation and convection losses (Sodha *et al.* 1987 in Ekechukwu & Norton 1999b), however, they are more expensive compared to bare flat plate solar collectors. These collectors are recommended for higher temperature uses.

The covered flat plate with a still air gap also consists of an air duct with an insulated rear surface and an extra layer of static air between the cover and the absorber plate. Soponronnarit (1990) studied bare and glass cover solar collectors. The results showed that the use of bare flat plate solar collectors is technically viable at low wind speed

and air speed inside collector should be 4 to 6 m/s with a corresponding air flow of 0.015 to 0.023 kg/s/m², while covered flat plate collectors could be used either at low or high wind speed with higher efficiency. Corrugated iron (CGI) sheets are often used for flat plate collectors (Ekechukwu & Norton 1999b; Lahsasni *et al.* 2004; Proctor 1994; Sharma *et al.* 1986; Soponronnarit 1988; Soponronnarit *et al.* 1986) due to their large surface area, wide availability and low cost.

3.3.1 Efficiency of collectors

The efficiency of the collector varies with the type of collector material used. Exell (1980) acknowledged that efficiency is not always known with certainty and assumed it to be 25% for estimation purposes. However, James (1992) and Sharma *et al.* (1986) assumed the efficiency of collectors as 40%. Soponronnarit *et al.* (1986) conducted an experimental investigation of efficiency of flat plate collector using CGI sheets at flow rate of 0.018kg/s/m². The minimum efficiency was recorded as 29%. Similar tests by same author in 1988 resulted in a collector efficiency of 30% and 34% for unpainted and black painted CGI sheets respectively (Soponronnarit 1988).

3.4 Solar drying of crops

Lutz *et al.* (1987) investigated the time taken to dry grapes using the traditional drying method and solar drying. Natural sun drying took 8 - 12 days to dry while solar dryers took 4 - 7 days depending on the weather conditions. Bala *et al.* (2003) also compared the drying time of pineapples with natural sun drying using tunnel dryers. The results found that it took three days to reduce moisture content from 87% to 14% using solar tunnel dryers while for same period using natural sun drying, the final moisture content was 21%, while Pangavhane *et al.* (2002) reported that drying times of grapes were reduced by 43% by a natural convection solar dryer compared to open sun drying.

Simate (2003) found that mixed mode natural convection drying required a shorter collector length (1.8 m) as compared to an indirect dryer collector (3.34 m) for the same grain capacity. Ivanova *et al.* (2003) estimated a saving of 17.7% of the annual heating load during the day by using solar energy to heat the working fluid of a solar

dryer. Farkas and Smith (1987) mentioned that by applying a microcomputer assisted automatic control system to solar dryers, product quality can be ensured at optimum use of available solar radiation. However such advanced technology would not be feasible in rural Bhutan.

3.4.1 Solar drying of chilli

Tiris *et al.* (1995) investigated the drying time of chilli peppers using the solar air heaters. The drying time was found to be shorter by 2.0 days using the solar air heaters in comparison to a natural sun drying which normally took 6 to 10 days to achieve same final moisture content, while Korel *et al.* (2002) reported a drying time of 14 days using natural sun drying. Furthermore, Singhagajen (1981) reported that the solar dryer reduced the drying time of chilli by one third of natural sun drying. Also, an experimental investigation found that solar drying reduced the drying time by 2.8 times compared to natural sun drying of chilli at a mass flow rate of 150 to 250 kg/m²h (Tiris *et al.* 1996). Reducing the thickness of drying material from 10 cm to 5 cm decreased the drying time by 30% (Dogantan *et al.* 1987). Also slicing of the chilli decreased the drying time by 60%. Further, Jensen *et al.* (1999) reported that it took 3 to 4 days to reach a final moisture content of 12% using natural convective solar dryers. Mastekbayeva *et al.* (2000) compared the drying time of green chilli using natural sun drying and a solar-biomass hybrid dryer. While the later required 21 hours to reduce moisture content from 76% - 6.6% wet basis, the former took five days to achieve same level of final moisture content.

3.4.2 Solar drying of beef

There is very little public information on drying of beef in general and solar drying in particular. Whatever literature is available is mostly based on the drying of meat by deep frying and on the meat based products. For example, Simal *et al.* (2003) studied the drying mechanism of meat based products like sobrasada and nothing was mentioned about the meat, while Lisse and Wack (1998) studied drying of meat by deep-fat frying. The later results indicated that frying time ranged from 17 to 90 minutes to reach a final moisture content of 8% from an initial moisture content of 56 -

80%. The time depended on the temperature of frying oil. Increasing the temperature of oil reduced the drying time by a factor of 2.3. Similarly, Mittal and Zhang (2001) used an artificial neural network to predict the temperature and moisture content of meatballs during deep-fat frying.

Holley (1985) investigated drying of meat jerky using an electric dehydrator. The results showed that the moisture content was reduced from 68% to 20% after drying for eight hours at 50°C. Also Jensen *et al.* (1999) reported that it took five days to reduce moisture content of meat from 65 to 12% using natural convective solar dryers in Ghana. Fuller and Lu Aye (2002) designed a solar assisted meat dryer. The dryer was designed to dry meat at 50°C for 10 hours from 400% (db) to 10% (db). The simulation results showed that the solar contribution to the load was 49%.

3.5 Back-up heating

Since solar energy is highly intermittent and variable, a back-up heating source is required to avoid growth of pathogens and moulds and re-absorption of moisture during the periods of low or zero solar radiation. Charters and Pryor (1982) noted that it is not economic to design a solar thermal system to support 100% load. This is mainly due to high cost of solar collectors and other accessories. Also it may be oversized during the high solar period. Thus a back-up energy source is necessary and should be able to provide full load during the poor weather periods. This will supplement solar energy during the day time and will provide 100% of the load if used during the night.

3.6 Scope for solar drying in Bhutan

As seen in Section 1.2, about 33% of the total chilli produced in Bhutan was traded in 2000 (MoA 2000). This includes both fresh and dried chilli. The loss of chilli due to inefficient drying in Bhutan is not reported and is still unknown. Dongantan *et al.* (1987) reported that in the K Moras district of Turkey about 20% of the total chilli harvest was lost as a result of inefficient traditional drying methods. In this researcher's experience, the loss due to inefficient drying in Bhutan may not be lower

than this value. In Bhutan, the farms are all family owned and there is no system of commercial farming. The chillies that are traded in the markets are all surplus production. Thus it is unlikely that every house can afford a solar dryer for their own use. So an alternative approach is to install a solar dryer in one village and operate on a cooperative yet commercial basis.

Moreover, the solar dryer may be less attractive if it is to be used for drying crops for household consumption. Also the cost of drying per unit of crops needs to be as low as possible so that the financial benefits of using a solar dryer are high. This requires that the technology proposed in every developing country makes use of local raw materials, traditional skills and local energy sources (Hodali & Bougard 2001). In line with this, Singh *et al.* (2004) designed a portable solar dryer, which could be dismantled, for use in villages. This included an option to dry the product under shade or without shade. The thermal efficiency was reported to be 28.5%. But one design may not suit the needs of different users in different places as the availability of solar energy varies with geographical area, with time of the year and with weather conditions. Thus it is desired that systems are designed to match the climate where they are going to be located, so a proper study is necessary before producing the dryers.

However, to study the performance of a solar dryer during different times of a year and at various locations requires climatic data for that location. Ali and Sakr (1981) claimed that at least ten years meteorological data is necessary to obtain a good average. A search of the literature revealed that Bhutan neither has a meteorological station nor has any attempt been made to generate climatic data. Thus, the first step in this study is to generate meteorological data for Bhutan using the methods available in the literature. Therefore Section 4 explains in detail the generation of meteorological data for Bhutan.

3.7 Conclusions

The different types of solar dryers have been explained in the preceding sections. The benefits of using solar dryers are immense but the acceptance of this is still very low in the developing countries. The reasons for the low acceptance rate call for appropriate

technology that suits the developing countries. Any proposed technology needs proper evaluation before implementing it. To assess the performance of a solar crop dryer requires meteorological data for the location proposed which Bhutan has none at the time of this study. Thus the next section describes the generation of meteorological data for Bhutan.

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4. GENERATION OF TMY DATA FOR BHUTAN

4.1 Introduction

In general, the long-term performance predictions of any solar energy system depends on the long-term climatic features of a location (Argiriou *et al.* 1999; Celik 2003; Ecevit *et al.* 2002; Gansler *et al.* 1994; Kalogirou 2003; Knight *et al.* 1991; Skeiker 2004; Zeroual *et al.* 1996) The need for and advantage of using a one year meteorological data file for evaluating the long-term system performance has led to the development of a Typical Meteorological Year (TMY), a term used in USA, or Test Reference Year (TRY) or Design Reference Year, terms used in Europe (Argiriou *et al.* 1999; Celik 2003; Ecevit *et al.* 2002; Satyamurty & Ravikumar 2004; Skeiker 2004).

Typical Meteorological Year data is a set of hourly values of solar radiation and meteorological elements for a period of one year generated from long-term observed data. Santos *et al.* (2003) claimed that meteorological variables are highly random for a short period of time like days and nights and highly deterministic for a long period of time like months and years. However, these data sets correspond to the occurrence and persistence of the weather in all months. TMY provides a standard hourly data of solar radiation and other meteorological elements that permit comparison of the performance of different solar energy systems and configurations for various locations. It does not indicate conditions over the next year, rather it represents conditions judged to be typical over a long period of time. Therefore, TMY data may not be suitable for designing systems to meet worst-case conditions occurring at a location.

Different countries have generated TMY data for various locations. However, at the time of this study, Bhutan neither has TMY data readily available nor any attempt has been made to generate TMY data. So, the first step in this study is to generate TMY data for Bhutan.

4.2 Methods of TMY data generation

The literature indicates that there are several methods to generate TMY data. Ecevit *et al.* (2002) summarised three different methods to generate TMY data. They are

- Danish method by Anderson *et al.* in 1977 and by Lund and Eidorff in 1981;
- Festa Ratto method in 1993;
- Sandia National Laboratory method by Hall *et al.* in 1978.

These methods have been explained in detail by Argiriou *et al.* (1999); Ecevit *et al.* (2002); Gazela & Mathioulakis (2001), so this study will not dwell on how each method works. However, these three methods mentioned above require long-term climatic data to generate TMY data for a particular location. Unfortunately, like most developing countries, Bhutan has no meteorological station, so long-term climatic data is not available. Thus, a different approach has to be used to generate TMY data for Bhutan.

Santos *et al.* (2003) suggested two methods for estimating meteorological variables when long term observed data are not available. The first method is by extrapolating from similar data from location with similar climatic conditions. A significant error has been reported using this method due to variations in climatic conditions. The second method is to generate the data synthetically from a limited set of input data. This method was developed by Knight *et al.* (1991) and was incorporated into the TRNSYS program (more about TRNSYS is explained in Section 5.5) as Type 54 weather generator.

This component uses monthly average values of solar radiation, dry bulb temperature, humidity ratio and wind speed to generate monthly weather data approximately equal to the TMY data of a location (TRNSYS 2003). This allows TRNSYS to be used for locations where detailed weather data is not available. The methodology used is not pursued in this study since it is well explained in detail by Knight *et al.* (1991). However, as mentioned by Knight *et al.* (1991), the method used for generation was developed for temperate climate data and the accuracy of the data generated is unknown for other climate data.

Although chilli is mainly grown in sub-tropical and warm temperate regions in Bhutan, the region under study is in warm temperate climatic regions. So the Type 54 weather generator can be used for solar simulation without further modifications. However, the Type 54 requires monthly average insolation, ambient temperature, wind speed and humidity ratio as inputs which Bhutan has none. Therefore these data have to be extracted from NASA.

NASA satellite data which gives average values for last ten years (NASA 2004a) has insolation uncertainties up to 17% (NASA 2004b), so the output from the Type 54 may further vary. Thus output from the Type 54 needs to be verified against known and measured values. In this case the measured value is TMY data. Therefore, output from the Type 54 using inputs from NASA will be compared to TMY data and further verified using average monthly long-term observed data as inputs to the Type 54.

4.3 Validation of Type 54 weather generator

The validation method is described in the following sections and illustrated in Fig 4.1.

4.3.1 Selection of locations

As Bhutan has no meteorological station, the Type 54 weather generator output has to be compared for some other location which has both TMY data and long-term average monthly observed meteorological data. However, the climatic features of the selected locations have to be similar to Bhutan's climate so that the same validation is applicable to Bhutan.

Thus, to make a realistic comparison, monthly average temperature and solar radiation were extracted from NASA for Bhutan and several other cities which are located at about the same latitude. From the plot of solar radiation and average temperature of Bhutan and other cities, it was revealed that the regions in the Himalayas like New Delhi, Kathmandu, Lahore and Lhasa exhibited the same pattern of climatic variation to that of Bhutan. However, these cities do not have TMY data and hence cannot be used.

Fig. 4.1. Flowchart for validating Type 54 weather generator

A further search revealed that Canberra, Hobart and Melbourne in Australia are found to be closer to Bhutan in terms of average monthly solar radiation and temperature and these cities do have both TMY data and long-term average monthly observed data for more than 10 years. Thus these three cities were selected as best possible location for validating the Type 54 weather generator. Fig. 4.2 and 4.3 shows the variation of solar radiation and temperature for three Australian cities and Bhutan. Since Bhutan is located in Northern Hemisphere, the X-axis has been adjusted to show the similar season to that of Australia (i.e. for Bhutan X-axis should be read from January, not July).

4.3.2 Validation inputs

As indicated in Fig 4.1, two sets of inputs are used for validation. The first set of inputs was taken from average monthly long-term observed (AMLTO) data (Unimelb 1980). The second set of input was extracted from NASA satellite (NASA 2004a) for the same latitude and longitude as the first set (see Appendix 3 & 4 for the detailed data set

used). These two sets of inputs were then used to generate yearly meteorological data from the Type 54 weather generator.

Fig. 4.2. Average monthly temperature

From the generated meteorological data, two sets of average daily solar radiations were extracted for two sets of inputs used. These values were compared with a set of average daily solar radiations extracted from TMY data from Morrison and Litvak (1999). Here TMY data is taken as the best case since TMY represents a typical year selected from long-term observed data and therefore is a universally accepted meteorological data model. Literature also reveals no or minimal variation in system performance using TMY data compared to long-term observed data. The results of the comparison are discussed in following paragraphs.

Fig. 4.3. Average monthly solar radiation

4.4 Comparative analysis

Solar radiation is the prime forcing function for any solar energy system (Sukhera *et al.* 1986). Thus the comparison of the data will be based on the average daily solar radiation. Fig. 4.4 shows the comparison of average daily horizontal surface radiation for three locations; Canberra, Hobart and Melbourne.

Solar radiation for all three different sets of data are close to each other. This is true for all the three locations. In fact, the yearly average solar radiation variation is minimal. Table 4.1 shows the root-mean-square deviation (RMSD) of solar radiation for inputs from NASA and AMLTO expressed as a percentage of solar radiation from TMY data. From the table it is evident that the inputs from NASA show a deficit of 10.8% for Canberra while it over-estimates for Hobart and Melbourne by 11.7% and 7.5% respectively. The inputs from AMLTO show a deficit of 3.2% for Canberra while it over-estimates for Hobart and Melbourne by 6% and 6.4% respectively.

The estimate of solar radiation using the Type 54 with AMLTO data is closest to the TMY data, and the variation is significant (i.e. greater than 10%) in case of inputs from NASA. The reason for this could be due to the source of the input data. NASA estimated uncertainties (RMS bias) of 18.5% for relative humidity, 3.2 % for air temperature and 10 to 17% for horizontal insolation (NASA 2004b) (see Appendix 5 for details). Further it states that the variation could be either positive or negative. As all these quantities are used as inputs to Type 54 weather generator, a variation in prediction may not be ruled out. Thus, appropriate values may need to be accounted for in the design calculations when using inputs from NASA.

Table 4.1: Yearly root-mean-square deviation of solar radiation

Inputs	Canberra	Hobart	Melbourne
NASA	-10.8%	11.7%	7.5%
AMILTO	-3.2%	6.0%	6.4%

(a)

(b)

(c)

Fig. 4.4. Comparison of average daily horizontal surface radiation generated using NASA and AMLTO with TMY (a) Canberra (b) Hobart (c) Melbourne

4.5 Conclusions

The Type 54 weather generator can be used for generation of TMY data for locations where meteorological stations are not available. As the accuracy of the Type 54 weather generator using NASA data as inputs was not known, it has been verified for three locations in Australia by comparing the average daily solar radiation generated by Type 54 weather generator using two different sets of inputs against standard TMY data available for a location. From the comparison, it was found that the percentage variation is less than 7% for inputs from long-term observed data and more than 5% for inputs from NASA. Thus it indicates that although the Type 54 weather generator can be used for solar simulations without any further modifications, it has to be used with caution when the inputs are from NASA satellite data.

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5. PERFORMANCE EVALUATION OF THE EXISTING SOLAR DRYER AT KHAO-KOR

5.1 Introduction

As stated in Section 1.4.2, the objective of this study is to evaluate a suitable solar dryer for drying agricultural products in Bhutan. The solar dryer should be financially and practically viable. To achieve these objectives, an existing commercial solar dryer installed at Khao-kor in Thailand (latitude 16.42°N and altitude 166 m above sea level) was selected. The selection was based on the following criteria:

- The existing solar dryer was successfully installed;
- The dryer was tested for varieties of products like basil, banana, turmeric, ginger, cabbage and chilli;
- The dryer is simple to operate.

Although the solar dryer installed at Khao-kor in Thailand has been successfully implemented, the same performance level may not be anticipated in Bhutan. This is largely due to the variations in the operating conditions particularly climate and quality interpretation (dryness) and the economic considerations.

Fig 5.1 shows the average annual solar radiation and ambient air temperature in Bhutan and Khao-kor. While Khao-kor is associated with high ambient air temperature and moderate solar radiation, Bhutan receives higher solar radiation but the ambient air temperature is much lower. The ambient temperature in Bhutan varies from -5 to 15°C whereas in Khao-kor the ambient temperature ranges from 20 - 28°C. While Khao-kor is in a tropical climatic region, the dryer in Bhutan is envisaged to be used in warm temperate and sub-tropical climatic regions. Thus a comprehensive evaluation is necessary to determine the technical and financial viability before replicating the Khao-kor type solar dryer in Bhutan.

Fig. 5.1. Comparison of radiation and ambient temperature in Bhutan and Khao-kor (NASA 2004)

5.2 Performance evaluation by simulation

Simulation is a design tool which can be used repeatedly for evaluating the performance of the system with different design parameters. Development of a simulation model is considered as a valuable tool for predicting the performance of solar cop dryers in various locations (El-Sebaai *et al.* 2002). Simulations can be performed to subject the system to extreme weather conditions and loads. Solar energy being highly transient, a theoretical model is a helpful and a necessary tool for researchers. Simulation provides an opportunity to assess alternatives and avoids full scale experimentation which is very expensive. A reliable model may prevent mistakes in development of a prototype.

Fuller *et al.* (1999) modeled the existing solar crop dryer in Thailand using the solar simulation software, TRNSYS (TRNSYS is described in Section 5.5) and the results of the simulation were found similar to the measured values. However, only six hours of data was used. Also Reuss and Benkert (1995) modeled a solar wood dryer using TRNSYS. The model was experimentally investigated at the same time. The observed differences were found within the expected range. Thus, in this study TRNSYS is used to evaluate the performance of the solar dryer system.

5.3 Parameters of performance evaluation

A search of literature revealed different methods to report solar dryer performance results. Grupp *et al.* (1995 in Leon *et al.* 2002) proposed a test from the users perspective and the parameters reported were the physical dimensions, type of dryer, solar aperture, tray area, drying time, drying temperature, final moisture content, dried product quality and ease of handling. Sodha and Chandra (1994) argued that in addition to the above parameters, cost, lifetime durability and maintenance requirements should be considered. Leon *et al.* (2002) reviewed different solar dryer evaluation parameters used in the literature (reproduced in Appendix 6). It is evident that different authors have used different parameters to evaluate solar dryers and no consistent method is available. Leon *et al.* (2002) compiled a set of parameters to report the solar dryer performance results, as listed below.

i. Physical features

- Type of dryer
- Size and shape of dryer
- Collector area and solar aperture
- Drying capacity, drying bed area and ease of loading and unloading

ii. Thermal performance

- Drying time/drying rate
- Drying temperature
- Relative humidity
- Air flow rate
- Dryer efficiency

iii. Quality of dried product

- Sensory quality (colour, flavour, taste, texture and aroma)
- Nutritional attributes
- Rehydration capacity

iv. Financial viability

- Cost of dryer and drying
- Payback period

The physical features of the dryer investigated in this study are assumed to be same as already installed in Khao-kor. The evaluation of the quality of dried product is beyond the scope of this study. Thus this study focuses only on the thermal performance and financial viability of Khao-kor type solar dryer replicated in Bhutan. Depending on the results of performance evaluation, the physical features may or may not need alteration.

5.4 Thermal performance evaluation

5.4.1 Physical features of solar dryer in Khao-kor

The solar drying system in Khao-kor consists of four batch type drying units. Each unit has a 73 m² collector area, 2 kW blower, 2.75 m² drying bed, air to steam heat exchanger and rectangular ducts (Fuller *et al.* 1999; Swasdisevi *et al.* 1999).

Swasdisevi *et al.* (1999) tested the dryer system experimentally while Fuller *et al.* (1999) modeled the solar dryer system and the simulation results were found similar with maximum variation of 5%. Table 5.1 summarises the parameters of the existing solar dryer at Khao-kor.

Table 5.1. Parameters of existing dryer at Khao-kor

Parameters	Unit	Value
Capacity of dryer	kg	100 -150
Collector area	m ²	73
Mass flow rate of air	kg/hr	3120
Velocity of air	m/s	0.75
Drying air temperature	°C	60
Drying bed area	m ²	2.75

Fig. 5.2 shows a schematic diagram of solar dryer at Khao-kor. The system has a blackened solar heat absorber that has a transparent cover and is well insulated on its lower side. As the air is sucked in through the collector, it is heated up by the heat generated due to solar energy absorbed by the collector. Further it is heated up by the steam to air heat exchanger if the air temperature was lower than the set value of 60°C. The heated air is then blown into the drying trough.

Fig. 5.2. Schematic diagram of solar dryer at Khao-kor

5.4.2 Drying periods

The drying periods of products are dependent on their availability during the year. While the chilli harvest is limited to two months a year, beef is available throughout the year and therefore can be dried any time. However, the drying period has to be chosen to maximise the use of solar energy.

a) Chilli drying

As chilli is harvested during the months of August and September, it is intended that the dryer will be used exclusively for drying chilli during these two months. The dryer will be simulated during these two months for chilli using the TMY data generated in Section 4. The average solar radiation during this period is $15.28 \text{ MJ/m}^2/\text{day}$. The time of drying is chosen to maximise utilisation of the solar energy available and minimise use of the auxiliary energy. Fig. 5.3 shows the average hourly global solar radiation during the months of August and September. The solar radiation is highest during the period 10 a.m - 5 p.m. However to select the best possible drying period, the time

taken to reduce the moisture content from 567% (db) to 10% (db) has to be determined. Thus, for the first drying cycle the dryer will start at 10 a.m and continue until the final moisture content of chilli is less than 10% (db) to determine the drying time. The subsequent drying cycle will be based on the required drying time, as determined from the first drying cycle.

Fig. 5.3. Average hourly solar radiation during the period August to September

b) Beef drying

As there is no particular season for drying meat, it can be dried on any day during the periods January to July and October to December. However, as per the Livestock Act of Bhutan (Dorji 2004b), slaughtering of animals and sale of meat in Bhutan is banned during the first and fourth months of Bhutan's Lunar calendar. The first month of the Lunar calendar in Bhutan falls on 15th February - 16th March and the fourth month falls from 17th May - 15th June. Thus during these two periods, meat cannot be dried. This indicates that although solar radiation is highest between March and June, this period cannot be fully utilised for drying meat due to the slaughter ban. Thus, meat can be dried during the periods 1st January to 14th of Feb, 17th March to 16th May, 16th June to 31st July and from October to December.

5.4.3 *Batch size*

a) **Chilli**

The quantity of chilli that could be dried per batch is assumed to be equal to the maximum capacity of the dryer i.e. 150 kg/batch. The chilli will be dried in thin layers without slicing or any other treatment before drying.

c) **Beef**

Since the principle product in this study is chilli, the same dryer parameters obtained for chilli will be used for drying beef. However, unlike chilli which is dried in layers, beef cannot be dried in layers as the air flow will be blocked and moreover, the surface in contact cannot be dried. Thus beef has to be dried by hanging with hooks over wires fixed on the surface of the dryer trough. Therefore, the quantity of beef that could be dried per batch is 100 kg/batch from Appendix 7.

5.4.4 *Supplementary energy source*

Since hydropower is the main source of energy in Bhutan, the use of any other energy sources is likely to be very expensive and may not be affordable to the rural people. Thus electricity is proposed as the supplementary energy source.

5.4.5 *Inclination of the solar collector*

Generally, the solar radiation absorbed by the surface depends on the angle of incidence which is the angle between the sun's rays and a line normal to the surface of the collector. This angle varies with the time of the year. Thus the inclination of collector depends on the drying season. For winter drying, latitude plus 10° - 15° gives the maximum solar energy available to the collector surface while latitude minus 10° - 15° gives maximum solar energy for the summer loads (Howell *et al.* 1982 p. 237). For year-round drying, a collector slope equal to the latitude angle gives the maximum solar energy to the collector surface (AIT 2004; Anderson 1983; Howell *et al.* 1982; USDA 1980). Thus a slope of 28° equal to the latitude angle of the location under study is used.

5.5 System model

The complete solar drying system has been modeled using TRNSYS (version 15.3). TRNSYS - Transient Simulation Programme is based on a modular approach where each module is a separate entity. The TRNSYS library includes the most common components used in a solar thermal energy system, modules to handle weather and output data. Each module can operate in several different modes. TRNSYS has the capability of interconnecting the system components in any desired manner. Moreover, any module can be easily added to the library without any further modifications. These features, i.e. adaptability and flexibility, make TRNSYS a comprehensive package to simulate solar thermal energy systems.

In this study, standard components were used from the TRNSYS library and functions of the components used in this study are explained in Appendix 8. The drying trough model which is not available in the TRNSYS library has been written separately using FORTRAN codes and exported to TRNSYS library using Compaq Visual Fortran and named as a Type 104. The subroutine is based on the mathematical expressions described in the next sections. This component computes the collector efficiency, system efficiency, pick-up efficiency, final moisture content and equilibrium moisture content. The source code of the subroutine is given in Appendix 9.

5.6 Modeling of dryer trough

5.6.1 Drying Rate

As reported in Section 2.3, drying rate for thin bed drying is based on Newton's law of cooling and is proportional to the difference between actual and equilibrium moisture contents (Equation 5.1) (Ekechukwu 1999; Erenturk *et al.* 2004; Hall 1957, 1980; Telis *et al.* 2004).

$$\frac{(M - M_e)}{M_o - M_e} = e^{-kt} \quad (5.1)$$

where M = Moisture content of sample (db)

M_e = Dynamic equilibrium moisture content (db)

M_o	=	Initial moisture content of sample (db)
k	=	Drying constant (min^{-1})
t	=	Drying time (min)

The drying constant ‘ k ’ is determined by experimental studies of moisture removal at different drying conditions. It is dependent on crop and drying air properties.

5.6.2 *Equilibrium moisture content*

The equilibrium moisture content of chilli is computed using the equation proposed by Kaleemullah (2002 in Kaleemullah & Kailappan 2004) (Equation 5.2). Kaleemullah and Kailappan (2004) studied the moisture sorption isotherms of red chillies using several equations i.e. Oswin (1946), Smith (1947), Halsey (1948), Henderson (1952), Day and Nelson (1965), modified Henderson (1968), modified Halsey (1976) and Kaleemullah (2002). It was found that the Kaleemullah equation (2002) best described the sorption isotherms of chillies.

$$M_e(db) = \left[\frac{\ln\{(Rh - a)/(-b)\}}{-(c \times T_c)} \right]^{(1/d)} \quad (5.2)$$

where Rh	=	Relative humidity (decimal)
T_c	=	Temperature ($^{\circ}\text{C}$)
a, b, c, d	=	Dimensionless constants

The values of constants a , b , c , and d as obtained by Kaleemullah and Kaillapan (2004) were used in this study to compute the equilibrium moisture content of chillies. They are:

$$\begin{aligned} a &= 0.8406; & b &= 0.8189 \\ c &= 0.000739; & d &= 1.4102 \end{aligned}$$

5.6.3 *Dryer efficiency*

The efficiency of a solar dryer is studied under three contexts: heat collection efficiency which is normally called as collector efficiency, system efficiency and pick-up efficiency.

a) Collector efficiency

The collector efficiency is the measure of collector performance in the dryer system. It measures how effectively the solar radiation incident on the collector area is transferred to the drying air flowing through it. This can be computed using the Equation 5.3 (AIT 2004; Leon *et al.* 2002)

$$\eta_c = \frac{m \times C_p \times (T_o - T_i)}{I \times A_c} \quad (5.3)$$

where m = Mass flow rate of air through collector (kg/hr)
 C_p = Specific heat of air (kJ/kg/°C)
 T_i, T_o = Inlet and outlet temperature of air (°C)
 I = Average solar radiation (kJ/m²/hr)
 A_c = Collector area (m²)

b) System efficiency

The system efficiency is the measure of how effectively the input energy to the dryer system is used to dry the product. It can be computed by Equation 5.4 (AIT 2004; Leon *et al.* 2002).

$$\eta_s = \frac{M_w \times L}{(I \times A_c) + P_b + E_s} \quad (5.4)$$

where M_w = Weight of water removed (kg)
 L = Latent heat of vaporisation of the product (kJ/kg)
 I = Average solar radiation (kJ/m²)
 A_c = Collector area (m²)
 P_b = Energy consumption of blower or fan (kJ)
 E_s = Supplementary energy consumption (kJ)

c) Pick-up efficiency

The pick-up efficiency is the ratio of moisture removed from the product by the air flowing through the drying trough to the maximum capacity of the air to absorb

moisture. The pick-up efficiency can be calculated by Equation 5.5 (AIT 2004; Leon *et al.* 2002).

$$\eta_p = \frac{W_o - W_i}{W_s - W_i} \quad (5.5)$$

where W_o = Absolute humidity of air leaving the drying trough (decimal)
 W_i = Absolute humidity of air entering the drying trough (decimal)
 W_s = Adiabatic saturation humidity of air entering the drying trough (decimal)

5.7 Financial evaluation

Economic and financial analysis is necessary for any long term project to determine the viability of a project in terms of its benefit to the investors and as well as to the society as a whole (Finnerty 1996). While financial analysis deals with the net return of the project in terms of monetary values, economic analysis deals with the benefits of the project to the society as a whole. Generally for government projects, both economic and financial analysis are undertaken while the private investors look at only the financial benefits (Yahmadi 2003).

The indices used for financial analysis of solar crop dryers are the cost of the dryer (fixed cost), the cost of drying (variable cost) and the payback period (Leon *et al.* 2002), however, these three indices do not take into account the time value of money which states that a dollar now is worth more than a dollar promised at some other time in the future. Thus an alternative approach is to use the discounted cash flow technique. The discounted cash flow analysis is a technique by which the future value of money is converted into present value by using the discount rate of a country, which is computed based on the interest and inflation rate of a country. This technique gives a more accurate result compared to the non-discounted technique. Therefore the discounted cash flow technique is used in this study to evaluate the financial viability.

5.7.1 Financial analysis parameters

The parameters of a financial analysis include discount rate, inflation rate, project life time and funding sources.

a) Discount rate

The real discount rate was calculated using the consumer price index in Bhutan (Appendix 10). From the calculation, the approximate real discount rate for Bhutan is 13% based on 2004 estimate.

b) Inflation rate

The inflation rate for Bhutan as estimated by National Bureau of Statistics of Bhutan based on the base year 2003 is 5% (Dorji 2004a). This is assumed to remain constant over the project life time.

c) Project life time

In this study project life time is assumed as fifteen years based on the life time of timber used for construction.

5.7.2 Discounted cash flow analysis

The discounted cash flow analysis involves computation of net present values (NPV), internal rate of return (IRR), benefit cost ratio (BCR) and simple payback period. Each of these are discussed in the following paragraphs.

a) Net present value

The net present value (NPV) is the difference between discounted benefits and the discounted total capital and operating costs of the system. From the NPV, investors can know whether the project is worth the investment before actually implementing the project. The projects with a positive NPV are considered to be financially viable while for a negative NPV, an alternative to the project should be investigated. The NPV can be computed using the Equation 5.6 (Rocklife 2004).

$$NPV = \frac{R \times [(1+i)^t - 1]}{i \times (1+i)^t} - \frac{-S}{(1+i)^t} - C_c - \frac{O_c \times [(1+i)^t - 1]}{i \times (1+i)^t} \quad (5.6)$$

where R	=	Revenue (US \$/year)
S	=	Residual value (US \$)
C_c	=	Capital cost (US \$)
O_c	=	Operating cost (US \$/year)
t	=	Project life time (years)
i	=	Real discount rate (decimal)

b) Internal rate of return

The internal rate of return (IRR) of a period is the most commonly used assessment criterion in project evaluation because it is comparable to the profit rate of a project. The IRR is the discount rate that makes net present value of cash flow equal to zero. Thus, IRR is the discount rate at which the NPV is zero

c) Benefit-cost ratio

The benefit-cost ratio (BCR) is the ratio of the sum of the project's discounted benefits to the sum of its discounted capital and operating costs. The BCR estimates the cost effectiveness of a proposed project. The project is considered cost effective if the BCR is greater than one. The BCR can be computed by Equation 5.7 (Rocklife 2004).

$$BCR = \left\{ \frac{R \times [(1+i)^t - 1]}{i \times (1+i)^t} \right\} / \left\{ \frac{O_c \times [(1+i)^t - 1]}{i \times (1+i)^t} + \frac{-S}{(1+i)^t} + C_c \right\} \quad (5.7)$$

5.7.3 Payback period

Payback period is also another index used in solar system economic analysis (Kreider *et al.* 1989). Simple payback period is the technique to compute the total number of years required to pay back the investments from the net benefits. This could be

computed by dividing the initial investment by annual savings after tax (Thumann 1984; Thumann & Mehta 1997). Although simple payback is easily understood, it does not take into account the effect of inflation and interest. Thus, this method should be used in conjunction with other decision making tools like net present value and internal rate of return. However, discounted payback period includes the time value of money and hence is more accurate as compared to the simple payback period (Ruegg & Short 1988).

5.8 Conclusions

The method and the parameters used for evaluating the performance of the existing solar dryer at Khao-kor have been explained in the preceding sections. Although there are four different categories of performance evaluation of solar dryers, only technical and financial evaluation have been used in this study. The complete dryer system has been modeled using TRNSYS and simulations were performed for chilli and beef using the TMY data generated in Section 4. The next section describes in detail the simulation results of the technical and financial feasibility of the Khao-kor type solar dryer in Bhutan.

5.9 References

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6. RESULTS AND DISCUSSION

6.1 Introduction

The complete solar dryer system has been described and then modeled as in Section 5. The simulation was performed for chilli and beef at a drying air temperature of 60°C, drying air velocity of 0.75 m/s and drying air flow rate of 3120 kg/hr. The TMY data generated in Section 4 was used as weather data for the simulations. Although the existing dryer at Khao-kor uses oil as a supplementary energy source, for the reasons cited in Section 5.4.4, it is proposed to use electricity for the dryer in Bhutan. Thus, the results of the performance evaluation discussed in the following sections apply to electricity as a supplementary energy source.

6.2 Thermal performance

6.2.1 Chilli drying

The simulation was performed during the period August to September for the location of Paro, Bhutan (latitude: 27.44°E; altitude: 3811 m). During this period, hourly solar radiation levels varied between 0.2 MJ/m² and 3.8 MJ/m², ambient air temperature ranged from 5.5°C - 24.7°C and ambient relative humidity from 64% - 98%.

a. Drying time

To determine the time taken to reduce the moisture content of chilli from 567% (db) to 10% (db), a simulation run was performed starting at 10 a.m and continuing until the moisture content was less than 10% (db) at various "*k*" (drying constant) values. A "*k*" value of 0.03 was found to give acceptable results. At this "*k*" value, the drying time is 18 hours (Fig. 6.1) which agrees with Sitthiphong *et al.*'s (1989) findings. Thus chilli drying will be spread over two days i.e. 9 hours in a day. At the end of first day (after 9 hours), the moisture content of chilli is reduced from 567% (db) to 150% (db). It was assumed that over night the chilli will reabsorb 10% of the moisture and hence the initial moisture content on the second day is 165% (db). The drying of chilli has to be

started at 9 a.m instead of 10 a.m to maximise the use of solar energy and end at 6 p.m. Thus, over the period August – September, 4.5 tonnes (150 kg/batch x 30 batches) of chilli could be dried with drying time of 2 days (18 hours).

b. Operating schedule

As the drying cycle of chilli determined in the preceding paragraph is two days (9 hours in a day) and the solar radiation is highest between 9 a.m to 6 p.m (Section 5.4.2), the dryer will be operated from 9 a.m to 6 p.m every day during the period August to September to dry chilli. The dryer has to be loaded manually in thin layers before starting the drying cycle and unloaded when the drying of the entire batch is completed i.e. 6 p.m on second day.

Fig. 6.1. Drying curve of chilli

c. Dryer efficiency

The hourly collector, pick-up and system efficiencies were computed using the Equations 5.4 to 5.6. The daily collector efficiency varied from 28 - 34% while average daily pick-up efficiency ranged from 21.4 – 24.4% during the period of drying. The average daily system efficiency ranged from 11% - 22%.

d. Solar contribution

The solar fraction which indicates the total solar contribution to the load is an important performance parameter of any solar energy system (Duffie & Beckman 1991). The total quantity of energy required to reduce the moisture content of 4.5 tonnes of chilli from 567% (db) to 10% (db) is 78 GJ, i.e. 17.3 MJ/kg of fresh chilli. The total solar contribution to the load is 19 GJ or 24.4% of the total energy required. Since the total solar energy is dependent on the climatic conditions of the location, the average solar contribution varies day to day. Fig. 6.2 shows the daily solar fraction during the period August to September. As can be seen, the average daily solar fraction varies from 3 - 54%. This suggests that on some days solar contribution to the load is very low. This is mainly due to low radiation i.e. 2.2 MJ/day on some days

Fig. 6.2. Daily solar fraction during the period August to September

e. Cost of supplementary energy

The cost of supplementary energy source is an important parameter which determines the financial viability of the solar crop dryer. The computation of supplementary energy cost was based on the present tariff of electricity in Bhutan. The Bhutan Power Corporation (BPC) charges a 3-block progressive tariff for low voltage (230 V, single phase or 440 V, three phase) consumers (BPC 2004).

Block I (up to 80 kWh/month)	: Nu 0.60/kWh (US \$ 1 $\cong$ Nu 45)
Block II (between 80 – 200 kWh/month)	: Nu 0.95/kWh
Block III (morethan 200 kWh/month)	: Nu 1.20/kWh

The total cost of supplementary energy for drying chilli from August to September is US \$ 453.

6.2.2 Beef drying

a. Drying time

Unlike the case of chilli, drying time of beef could not be determined due to the non-existence of a drying constant in the literature and experimental determination was beyond the scope of this study. Thus drying time of beef is assumed as 8 hours based on the assumptions used by other researchers as discussed in Section 3.4.

b. Operating schedule

Although the solar radiation is highest between 10 a.m to 5 p.m (Section 5.4.2), the drying time of beef is 8 hours from the preceding paragraph, thus the operation of the dryer has to be extended by one hour more. The solar radiation from 9 – 10 a.m and 5 - 6 p.m are equal and thus beef drying can be either from 9 a.m – 5 p.m or from 10 a.m – 6 p.m. In this study beef drying is selected to be 9 a.m – 5 p.m. Therefore, the dryer will be operated from 9 a.m to 5 p.m daily during the periods 1st January to 14th of Feb, 17th March to 16th May, 16th June to 31st July and from October to December. The dryer has to be loaded manually by hanging the beef strips over the wires fixed over the surface of dryer trough before starting the drying cycle and unloaded when the drying of entire batch is completed i.e. 5 p.m.

c. Solar contribution

The total energy required to reduce the moisture content of 24.4 tonnes (i.e. 100 kg/batch x 244 batches) of fresh beef from 400% (db) - 10% (db) is 291.7 GJ, i.e. 12 MJ/kg. The total solar contribution to the load was 69 GJ or 23.6% of the total load. However, as in the case of chilli, a significant variation in solar contribution could be

observed. The maximum daily average solar contribution is 49% while for some days in January, November and December, the solar contribution is zero (Fig. 6.3).

Fig. 6.3. Daily solar fraction during the periods 1st January to 14th of Feb, 16th March to 14th May, 16th June to 31st July and from October to December.

d. Cost of supplementary energy

The total cost of supplementary energy for drying beef is US \$ 1752.

Table 6.1 summarises the results of thermal performance of the Khao-kor type solar dryer in Bhutan compared to that of the experimental investigation of drying chilli at Khao-kor by Swasdisevi *et al.* (1999). From the table, it shows that solar contribution to the load at Khao-kor is 53.5% while it is only 24% in Bhutan. The drying time of chilli in Khao-kor was 5.5 hours while it took 18 hours to dry in Bhutan. The longer drying time is due to fact that the chilli at Khao-kor was dried by slicing while the chilli in Bhutan has to be dried without any prior treatment or slicing. The collector and system efficiencies are approximately equal in both Khao-kor and Bhutan. However, there is significant difference of pick up efficiency. The high pick up efficiency could be due to short drying time for sliced chilli in Khao-kor. The total energy required for drying 4.5 tonnes of chilli and 24.4 tonnes of beef in Bhutan is 369.6 GJ. The total solar contribution to the load is 24%.

Table 6.1. Thermal performance of Khao-kor type solar dryer in Bhutan

Parameters	Unit	Average Value in Bhutan		Results at Khao-kor for chilli
		Chilli	Beef	
Drying time	hours	18.0	8.0	5.5
Pickup efficiency	%	23.0	n.a	39.7
Collector efficiency	%	30.0	40.0	46.4
System efficiency	%	14.5	17.0	19.3
Total solar energy	GJ	19.0	68.8	0.369
Solar fraction	%	24.4	23.6	53.5
Total supplementary energy	GJ	58.9	222.9	0.321
Cost of supplementary energy	US \$	453.4	1752.2	-

(Chilli is simulated for the period Aug to Sep while beef is for the periods 1st Jan to 14th of Feb, 17th Mar to 16th May, 16th Jun to 31st Jul and Oct to Dec)

6.3 Financial analysis

The following general assumptions were used for analysis:

- Constant discount rate and inflation over the project life time
- A constant electricity price over the project life time
- There is no tax levy on the dried products
- The price of fresh product is constant through out the season in a year.
- The dried products could be sold in the market.
- The consumers are willing to pay higher price for better product.
- Capital investment fund is available

6.3.1 Capital cost

The major cost of solar dryer includes cost of collector, drying trough and support structures. Based on the schematic diagram in Fig. 5.2, the quantities of materials are estimated and a corresponding cost was calculated. The estimate of the total cost of Khao-kor type solar dryer in Bhutan is shown in Table 6.2 (refer Appendix 11 for itemised cost). The prices of the different items used in the study are directly quoted from the Bhutan schedule of rates (BSR)-2001 (SQCD 2001). Since the rates in BSR were for the year 2001, 5% inflation per year (based on general practice in Bhutan)

was assumed to reflect the price in the year 2004. The prevailing exchange rate for the current year obtained from the Royal Monetary Authority of Bhutan (RMA) (RMA 2004) was used to convert the cost in terms of US dollars (refer Appendix 12). For the items like the blower and electric duct heater which were not available in the BSR, prices were obtained directly from dealers in India. As per the dealers, these prices are approximate and the actual price may differ depending on the scope of the project.

From the Table 6.2, the total cost of the complete solar dryer system in Bhutan is US \$ 2343.

Table 6.2: Cost estimate of solar dryer system

Parameters	Amount (US \$)
Land clearing and flooring	148
Solar collector and accessories	1 039
Dryer trough and frame	138
Duct heater, blower and ducts	817
Installation and labour cost	199
Total	2 343

6.3.2 Operational cost

The operational cost includes the supplementary energy cost, salary for the operators and cost of fresh products to be dried. The daily operational cost varies depending on the solar fraction. From Table 6.3, the annual operating cost is US \$ 34 977 combining both chilli and beef drying.

6.3.3 Cost- benefit analysis

The cost benefit analysis was done based on the prevailing market prices for both the fresh and the dried products in Bhutan. Table 6.3 shows the cost-benefit analysis of the Khao-kor type solar dryer in Bhutan (refer Appendix 13 for chilli only and Appendix 14 for chilli and beef combined). The annual net income was computed based on the number of drying batches/year, unit cost of fresh chilli and beef and selling price of dried chilli and beef. The cost of fresh chilli and beef are US \$ 1 and 1.2/kg

respectively. While the maximum selling price of dried chilli and beef are US \$ 5 and 5.4/kg respectively (Wangmo 2004). As there is no price regulation at present, these prices differ according to the quality and season of products sold (Wangmo 2004). From the table, it can be seen that the NPV is negative for both chilli and beef combined and hence no payback period. The negative value indicates that there is no net return from the investment in solar dryer and thus the system is financially not viable for investment in Bhutan. Also, the BCR is less than one. This further suggests that the system is not worth the investment.

Table 6.3. Cost-benefit analysis

Parameters	Amount (US \$)	
	Chilli only	Combined
Capital cost	2 343	2 343
Operating cost	4 943	34 977
Benefits	3 682	33 121
Discounted cash flow analysis		
Discounted revenue	23 796	214 043
Discounted O & M cost	31 941	226 037
Net present value	-10 413	-14 262
Benefit cost ratio	0.70	0.94
Internal rate of return	-	-
Discounted payback period	-	-

Summarising the results of performance evaluation, it can be seen that although the thermal performance of the Khao-kor type solar dryer is satisfactory in Bhutan, the system is not financially feasible for replication in Bhutan. Further, it is evident that the cost of supplementary energy source is rather high and depends on the size of system and also on duration and time of use. The alternative options are to increase the price of the dried products or to reduce the use of supplementary energy source. The reduction in supplementary energy may be achieved by using a lower drying air temperature or increasing the collector area. While reduction in drying air temperature will increase the drying time of both chilli and beef, over-sizing of the collector will make the system too expensive and may still not be affordable. Also, the prices of the

dried products are beyond the control of the dryer owner. Thus an alternative option is to minimise the cost of the drying by optimising the complete solar dryer system.

6.4 Optimisation

The purpose of optimisation in this study is to find the area of the collector that gives minimum annual drying cost. The overall cost of the system comprises of two different costs as shown in Equation 6.1 i.e. annual cost of dryer system cost and supplementary energy cost (Kreider *et al.* 1989). Both the costs depend on the size of the collector.

$$C_{tot} = C_a + C_f \quad (6.1)$$

where C_{tot} = Total cost expressed on annual basis (US \$/year)
 C_a = Annual cost of dryer system (US \$/year)
 C_f = Annual cost of supplementary energy (US \$/year)

Audsley and Wheeler (1978) proposed an equation to compute the annual cost based on the initial capital cost, salvage value of the materials and repair and maintenance cost. This Equation 6.2 has been used by Hossain *et al.* (2004) and Simate (2003) to optimise the solar crop dryers.

$$C_a = \left(C_i + \sum_{i=1}^n m_i w^i - S_n w^n \right) \times \frac{(w-1)}{w \times (w^n - 1)} \quad (6.2)$$

$$w = \frac{1+g}{1+r}$$

Where, C_i = Initial capital cost (US \$)
 m_i = Current value of maintenance cost in i^{th} year (US \$)
 S_n = Current value of residual value (US \$)
 n = Project life time (years)
 g = Inflation rate (%)
 r = Interest rate (%)

Further the initial capital cost comprises of two different costs, fixed cost and a variable cost which is dependent on collector area and is explained in the next section.

6.4.1 Optimisation procedure

The process of optimisation in this study is described below.

- i. The first step is to calculate the annual cost of dryer system as explained below.

- **Fixed cost**

The fixed cost includes the cost of electric duct heater, blower, ducts and dryer trough. The fixed and variable costs are calculated in Table 6.4. The fixed cost is US \$ 1174.

- **Variable cost**

The variable cost comprises of cost of collector, insulation, glazing, support structures and paint. The variable cost is US \$ 16/m².

Table 6.4: Fixed and variable cost

Particulars	Fixed cost	Variable cost
	US \$	US \$
Land clearing	111	37
Collector accessories	0	1 039
Dryer trough	138	0
Heater and blower	817	0
Installation	107	104
Total	1 174	1 180
Per unit cost (US \$/m ²)	-	16

- **Maintenance cost**

The annual maintenance cost is assumed as 2% of the total capital investment and further assumed to incur after every five years of operation.

- **Salvage value**

As the life time of CGI sheets are more than 20 years, the salvage value is assumed as 20% of the initial investment.

- ii. A collector area is selected and system is simulated for both the chilli and beef for entire periods mentioned in Section 6.2.1 and 6.2.2. Based on the simulation results, the cost of supplementary energy and total annualised cost determined (Appendix 15).

- iii. This calculation sequence is repeated until a minimum point of total cost is found.

In this study, the calculation was done in the steps of 10 m² and maximum collector area of 200 m². Fig A.3 shows a plot of the collector area and the annualised total cost.

Fig. 6.4. Plot of annual cost and solar collector area

From the figure, it can be seen that the optimum size of the solar collector is 140 m². At this collector area, the annualised total cost of the system is US \$ 2446. If the system were to use electricity only without any solar components then the annualised total cost is US \$ 2894.

6.4.2 Optimised performance

The optimised system has been simulated for both chilli and beef, i.e. 30 and 244 batches of chilli and beef per year respectively. The optimised thermal performance is depicted in Table 6.5. The optimisation increased average annual solar contribution of the system from 24% to 33% of the total load (and therefore decreased annual supplementary energy cost from US \$ 2206 to US \$ 1985).

Table 6.5: Thermal performance of optimised system

Parameters	Unit	Average value	
		Chilli	Beef
Drying time	hours	18.0	8.0
Pickup efficiency	%	15.8	n.a
Collector efficiency	%	30.6	48.0
System efficiency	%	18.7	17.0
Total solar energy	GJ	26.7	94.5
Solar fraction	%	33.6	32.2
Total supplementary energy	GJ	52.7	199.3
Cost of supplementary energy	US \$	408.0	1577.2

A cost-benefit analysis of the optimised solar dryer is compared with electric heating system and is summarised in Table 6.6 (detail in Appendix 16). The NPV of solar system is higher than the electric heating system which indicates that the solar dryer system is likely to be more feasible compared to an electric heating system. However, from the table it can be seen that the NPV of both the systems are negative. The negative values indicate that neither of the systems are financially viable in Bhutan.

Table 6.6: Cost-benefit analysis of optimised system

Parameters	Amount (US \$)	
	Solar system	Electrical heating system
Capital cost	3 437	1 174
Operating cost	34 751	35 506
Benefits	33 121	33 121
Discounted cash flow analysis		
Discounted revenue	214 043	214 043
Discounted O & M cost	224 572	229 455
Net present value	-13 856	-16 549
Benefit cost ratio	0.94	0.93
Internal rate of return	-	-
Discounted payback period	-	-

6.4.2 Drying cost

The drying cost C_d of any product is given by Equation 6.3 as the ratio of annual cost to quantity of product dried per year (Radajewski *et al.* 1987).

$$C_d = \frac{\text{Annualised total cost}}{\text{Quantity of product dried per year}} = \frac{C_{tot}}{Q_p} \quad (6.3)$$

The annualised cost for the optimised system is US \$ 2446 as calculated in the preceding sections. The drying costs for solar system are US \$ 7.94 and 5.96 per kg dry matter for chilli and beef respectively. The corresponding costs for electrical heating system is US \$ 7.76 and 6.25 per kg of dry matter for chilli and beef respectively.

From the comparison of the costs of the dry matter of chilli and beef in Table 6.6, the cost of fresh chilli is US \$ 6.67/kg of dry matter while the cost of dried chilli is US \$ 5.58/kg of dry matter. This indicates that at 10% final moisture content, dried chilli fetches lower price than the fresh chilli. The reason for this could be that the final moisture content of dried chilli in the local market in Bhutan may be higher than the 10% assumed in this study. Thus an alternative approach is to investigate the moisture content of dried chilli and beef in the local market in Bhutan, and then another analysis can be performed to determine the financial viability of the solar dryer system. The complete system would be financially viable if the final moisture content of chilli and beef are assumed as 15% (db).

Table 6.7: Cost of chilli and beef

Product	US \$/kg of dry matter	
	Solar dryer	Electrical heating system
Fresh chilli	6.67	6.67
Drying cost of chilli	7.94	7.76
Dried chilli	5.58	5.58
Fresh beef	5.83	5.83
Drying cost of beef	5.96	6.25
Dried beef	6.17	6.17

6.5 Conclusions

The thermal and financial performance of Khao-kor type solar dryer has been evaluated in the preceding sections for replication in Bhutan. The system has been optimised to minimise the annual drying cost. Although the potential for using solar dryer is high in Bhutan, from the financial evaluation it is evident that the Khao-kor type solar drying is financially not viable in Bhutan. Further, a complete electric heating system is also not viable financially. However, compared to the non-solar system dryer, a solar dryer is more attractive. Further analysis is required to determine the dryness of the dried chilli and beef sold in the local market in Bhutan, and then another analysis can be performed to determine the financial viability of the solar dryer system.

6.5 References

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7. RECOMMENDATIONS AND CONCLUSIONS

7.1 Recommendations

The development of solar dryers in Bhutan should be encouraged. The potential for using solar dryers is high in Bhutan. It is suggested that significant support should be provided for the development of solar dryers. Subsidies in the form of exemption from sales tax on CGI sheets and timber could reduce the cost of dryers.

From the technical and financial evaluation of the Khao-kor type solar dryer, the following are recommended for adaptation for Bhutan.

- The physical dimensions, drying temperature and air flow rate are recommended to remain the same as the thermal performance of the dryer is satisfactory. However, the collector area needs to be increased to 140 m² for the system to be viable at proposed final moisture content of dried chilli and beef at 15% (db).
- Although the dryer at Khao-kor has four drying units, only one unit is recommended for use in Bhutan.
- For the reasons cited in preceding sections, an electric heater is recommended as a back-up heating source.
- Batch size of chilli is 150 kg and can be dried in thin layers.
- Batch size of beef is 100 kg and has to be dried by slicing into strips.
- The dryer trough needs to be modified with wires on the top surface for hanging beef.
- The dryer has to be operated from 9 a.m – 6 p.m during the period August to September to dry chilli.
- Beef could be dried from 9 a.m – 5 p.m during the periods 1st January to 14th of Feb, 17th March to 16th May, 16th June to 31st July and from October to December.

7.2 Conclusions

Globally drying is the most widely used method for preserving food for use in the home or for sale. The drying process consists of evaporation of water content of product from the surface to the surrounding medium and movement of water from inside the product to the surface by means of diffusion. Air is used both as a medium to transfer heat to the product as well as to carry away the water from the surface. However, air has to be heated to certain level of temperature based on safe drying temperature to increase the moisture absorption capacity. The heating of air can be achieved by using any conventional heaters but these are expensive to run. Thus solar dryers are preferred for their inexpensive operating cost.

The different types of solar dryers have been explained in the Section 3. Although the benefits of using solar dryers are immense, the acceptance level is still low. The reasons for low acceptance rate calls for appropriate technology that suits the developing countries. Any proposed technology needs proper evaluation before implementing it. To assess the performance of a solar crop dryer requires meteorological data for the location proposed of which Bhutan has none at the time of this study. Thus the Type 54 weather generator has been proposed to use for solar simulation in Bhutan. The outputs of the Type 54 weather generator have been validated for inputs from NASA and AMLTO in Section 4. The results of validation indicate that the Type 54 can be used for simulating solar energy systems where meteorological data has not been observed. However, when the inputs to the Type 54 are extracted from NASA, the variation is significant and thus one needs to be cautious while designing solar energy systems.

An existing solar dryer at Khao-kor, Thailand has been evaluated for possible adaptation in Bhutan. The system has been modeled using TRNSYS (version 15.3). The subroutine for the dryer trough which is not available in the TRNSYS library has been modeled using visual FORTRAN and exported to TRNSYS as a Type 104.

The technical performance of the dryer was found satisfactory, however from the business point of view; the dryer is financially not viable in Bhutan. Nevertheless compared to the non-solar system dryer, solar dryer is more attractive than the non-

solar system. The total investment cost for a non optimised solar dryer is US \$ 2343. The corresponding cost for an optimised system is US \$ 3437 and for an electric heating system dryer is US \$ 1174. The NPV of the optimised solar system dryer is US \$ -13 856 while NPV of an electric heating system dryer is US \$ -16 549. The negative NPV is unlikely to attract private investors.

The benefits of using any dryer is small as there is only small price difference between fresh and dried products. Unless the price of the dried products is increased, it is unlikely that any commercial dryer would be viable in Bhutan. Nevertheless, the potential for using solar dryers is high in Bhutan. With average solar radiation of 16.6 MJ/m²/day, the solar dryer in this study can contribute about 33% of the load. In spite of high solar contribution, the system is still not viable. This is mainly due to the low price of the dried products especially chilli. From the comparison of the price of dry matter for both fresh and dried beef, it is more likely that the final moisture content of dried chilli sold in the local market in Bhutan is more than 10%. Thus the proposed dryer could be viable if the final moisture content of chilli and beef is maintained at 15% (db).

Chilli and beef are used in the evaluation of the dryer because they are popular and traditionally sun dried. There are no apparent reasons why other crops currently sun dried could not be dried successfully in the proposed dryer provided the safe drying temperature is not less than 60°C.

However, the complete analysis is based on the meteorological data generated by the Type 54 weather generator using average data from NASA as inputs. Since the data from NASA are not as accurate as ground measurement, the results may vary compared to the real ground measurements.

7.3 Further studies

This study has given rise to the following areas which need further study and analysis.

- Moisture content of dried chilli and beef available in the local market in Bhutan.
- Sale of dried chilli and beef to predict further financial viability.
- A similar study for different crops and regions of Bhutan.
- Experimental verification of the proposed solar dryer system by building prototype before implementing full dryer system to verify the simulation results.

APPENDICES

Appendix 1: Country Background

Bhutan – a rugged mountainous country lies sandwiched between India on the South, East and West and the Tibetan part of China on the North (CSO 2003). Bhutan is located between 26°45' North to 28°10' North latitude and 88°45' East to 92°10' East longitude (Yuden 2000). It comprises a land area of 38 394 square kilometres with 72.5% under forest cover. The country has a population of only 716 424 as per the census in 2002 and about 21% of people live in the urban areas (CSO 2003). About 80% of the population depends on agriculture for daily life and only 7.7% of the total area is used for agriculture. The altitude varies from 100m in the south to 7 500 m in the northern regions (CSO 2003).

Bhutan has three main land structures; the southern foothills rising from 100m to 1500 m above sea level. This region is mostly covered with thick forests. The central region of Bhutan rises from 1500m to 3000m above sea level. This region is considered as the economic heartland of Bhutan. The northern region comprises Himalayan ranges and rises up to 7500m above sea level (CSO 2003). Bhutan has a scattered settlement pattern and is sparsely populated. The entire country is divided into twenty districts for administrative purposes. The districts are further divided into blocks and villages.

Firewood has traditionally been the major source of domestic energy in Bhutan. Although it still represents the major domestic energy consumption, the trend for firewood usage is on decline due to the availability of cheap electricity from hydropower. Hydroelectricity contributed 56% of total commercial energy consumption in 2001 (CSO 2003). Bhutan has no reserves of any fossil fuel resources; so all petroleum products are imported. Bhutan's annual domestic consumption of electricity increased from 338 MWh in 1995 to 532 MWh in 2000 (PCS 2002). Bhutan exports 75% of total electricity generated to India.

Appendix 2: Total chilli produced and traded in 2000

District	Quantity produced (tonne)	Quantity traded (tonne)
Bumthang	28.9	3.7
Chhukha	150.9	86.7
Dagana	32.4	3.2
Gasa	11.9	0.9
Ha	10.6	0.3
Lhuentse	151.3	2.6
Mongar	154.4	23.8
Paro	707.8	347.6
Pemagatshel	74.3	16.3
Punakha	363.2	142.0
Samdrupjongkhar	44.9	3.7
Samtse	5.1	1.0
Sarpang	22.5	2.8
Thimphu	175.6	69.1
Trashigang	237.8	44.0
Trashiyangtse	136.4	24.0
Tsirang	48.1	9.7
Trongsa	99.3	27.7
Wangdiphodrang	365.5	115.8
Zhemgang	27.5	1.3
Total	2 849	926

Source: (MoA 2000)

Appendix 3: Input data from NASA satellite

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Canberra, Latitude: 35° 19' South; Longitude : 149° 11' East												
Monthly average daily global horizontal radiation (kJ/m ²)	23 688	20 988	17 532	12 672	9 288	7 884	8 424	11 160	15 264	19 584	22 392	23 508
Monthly average humidity ratio (g water/kg air)	12.2	12.1	10.8	9.2	7.8	6.5	6.1	6.5	7.6	8.9	10.1	11.4
Wind speed (m/s)	3.58	3.56	3.44	3.56	3.53	3.93	4.28	4.38	4.09	4.04	3.58	3.59
Monthly average temperature (° C)	19.8	19.6	17.5	14.3	11.2	8.0	7.0	8.0	10.3	12.9	15.1	17.5
Hobart. Latitude: 42° 53' South; Longitude : 147° 20' East												
Monthly average daily global horizontal radiation (kJ/m ²)	21 492	19 188	14 580	9 828	6 444	5 184	6 048	8 676	12 960	17 208	21 312	22 248
Monthly average humidity ratio (g water/kg air)	8.7	8.4	8.2	7.6	6.8	6.0	5.9	6.0	6.5	7.2	7.9	8.5
Wind speed (m/s)	5.71	5.60	5.55	5.77	5.99	6.67	6.64	6.73	6.60	6.45	5.86	5.61
Monthly average temperature (° C)	15.50	15.20	14.30	12.60	10.30	8.22	7.78	8.10	9.21	10.70	12.40	14.00
Melbourne, Latitude: 37° 49' South; Longitude : 144° 58' East												
Monthly average daily global horizontal radiation (kJ/m ²)	24 408	22 392	17 136	12 240	8 244	6 624	7 344	10 044	14 184	18 972	22 608	23 256
Monthly average humidity ratio (g water/kg air)	10.5	10.3	9.7	8.3	7.3	6.3	6.1	6.3	7.2	8.4	9.4	10.4
Wind speed (m/s)	3.53	3.46	3.29	3.43	3.32	3.60	3.70	4.07	3.72	3.71	3.52	3.49
Monthly average temperature (° C)	18.7	19.2	17.5	13.9	10.6	8.0	7.3	7.9	10.0	12.4	14.5	16.7

Source: (NASA 2004a)

Appendix 4: Input data from long-term observed data

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Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Canberra, Latitude: 35° 19' South; Longitude : 149° 11' East												
Monthly average daily global horizontal radiation (kJ/m ²)	25 890	23 280	18 510	14 420	11 020	8 630	9 540	12 720	17 830	21 120	24 870	26 690
Monthly average humidity ratio (g water/kg air)	8.4	8.8	8.0	6.7	5.7	4.9	4.4	4.6	5.4	6.1	6.8	7.5
Wind speed (m/s)	3.27	2.92	2.82	2.82	2.90	3.17	3.47	4.07	4.22	4.31	4.06	3.83
Monthly average temperature (° C)	20.3	19.6	17.5	13.1	8.7	6.4	5.3	6.7	9.2	12.4	15.3	18.4
Hobart, Latitude: 42° 53' South; Longitude : 147° 20' East												
Monthly average daily global horizontal radiation (kJ/m ²)	23 190	19 940	15 130	10 610	6 650	5 090	5 510	8 480	13 150	17 960	20 790	23 190
Monthly average humidity ratio (g water/kg air)	7.8	7.9	7.6	7.3	6.2	5.6	5.2	5.6	6.0	6.8	7.4	8.0
Wind speed (m/s)	5.13	4.78	4.44	4.29	3.75	3.56	3.75	4.22	5.01	5.29	5.42	5.39
Monthly average temperature (° C)	16.4	16.5	15.2	12.8	10.4	8.4	7.9	8.9	10.6	12.1	13.7	15.2
Melbourne, Latitude: 37° 49' South; Longitude : 144° 58' East												
Monthly average daily global horizontal radiation (kJ/m ²)	24 870	21 460	16 690	11 580	7 270	6 250	6 930	9 650	13 170	18 170	21 920	24 190
Monthly average humidity ratio (g water/kg air)	8.7	9.2	8.5	7.6	6.8	6.1	5.7	5.7	6.1	6.7	7.4	8.7
Wind speed (m/s)	3.63	3.43	3.21	3.14	3.15	3.15	3.22	3.60	3.86	4.09	4.13	3.92
Monthly average temperature (° C)	19.8	19.8	18.3	15.2	12.4	10.2	9.9	10.6	12.3	14.3	16.3	18.7

Source: (Unimelb 1980)

Appendix 5: Accuracy of NASA data

NASA compared values obtained from satellites with ground site measurements. The uncertainty estimates were done for insolation, temperature, surface pressure, relative humidity and wind speed. The estimated root mean square (RMS) bias and the methods used are given below.

Parameter	Method	RMS (Bias)
Horizontal Insolation	SSE satellite-based Staylor	10 to 17% (+3%)
Horizontal Diffuse Radiation	SSE/Erbs et al. correlation	~18% (+4%)
	SSE/Extended Page (74 reference sites)	~20% (+3%)
Direct Normal Radiation	SSE/RETScreen-type (hourly angular conversion)	~15% (-9%)
	SSE/Extended Page (empirical Staylor angular conversion)	~24% (+2%)
Flat, Rough Grass Wind (10-m height)	Documented 10-m height airport sites	1.3 m/s (-0.2 m/s)
	Unknown-height airport sites	1.3 m/s (-0.0 m/s)
	Global sites <243K	3.2% (NA)
	Global sites >263K	1.1% (NA)
Air Temperature, K (10-m height)	Global sites between 243K and 263K	linear variation
	200 potential renewable energy sites	1.2% (NA)
	in 7 continental regions	
Relative Humidity, %	Global	18.5% (NA)
	200 potential renewable energy sites	10% (NA)
Surface Pressure, kPa	Global	3.8% (NA)

Source: (NASA 2004b)

Appendix 6: Solar dryer performance evaluation parameters in the literature

Authors	Drying time/rate	Drying temp.	Air flow rate	Drying capacity	Quality of dried product	Energy consumption for drying	Cost of dryer/pay back	Temp. & RH of air	Loading/unloading convenience	Others
Arinze <i>et al.</i> , 1999	✓	✓	✓	✓	✓	✓	✓	✓	-	Collector efficiency
Das & Kumar, 1989	✓	✓	✓	✓	✓	-	-	✓	-	
Esper <i>et al.</i> , 1996	✓	-	✓	✓	✓	-	✓	-	-	
Fuller <i>et al.</i> , 1990	-	✓	✓	✓	✓	-	-	-	-	
Fuller, 1995	✓	✓	✓	✓	-	✓	-	-	-	
Gallali <i>et al.</i> , 1999	✓	✓	-	-	✓	-	-	-	-	Sensory evaluation
Gnanaranjan <i>et al.</i> , 1997	✓	✓	✓	✓	✓	✓	✓	-	-	
Grupp <i>et al.</i> , 1995	✓	✓	✓	✓	✓	-	✓	-	✓	Tray area, drying temperature control
Janjai <i>et al.</i> , 1998	✓	✓	-	✓	✓	-	✓	-	-	
Mande <i>et al.</i> , 1993	✓	✓	✓	✓	✓	✓	-	✓	-	Thermal efficiency
Martinez, 1989	✓	-	-	✓	-	-	-	-	-	Collector area
Mastekbayeva <i>et al.</i> , 1998	✓	✓	✓	✓	✓	-	✓	-	-	
Moyls, 1986	✓	-	✓	✓	-	-	-	✓	-	
Pairintra <i>et al.</i> , 1996	✓	✓	✓	✓	-	✓	✓	-	-	
Pengpad & Rackwichian, 1998	✓	✓	✓	✓	✓	✓	-	-	✓	Drying efficiency
Rahardjo, <i>et al.</i> , 1983	✓	✓	✓	✓	✓	-	-	-	-	
Rakwichian <i>et al.</i> , 1998	✓	✓	✓	✓	-	✓	-	-	-	Collector and dryer efficiency, fuel savings
Schirmer <i>et al.</i> , 1996	✓	✓	✓	✓	✓	-	✓	✓	-	
Sharma <i>et al.</i> , 1986	✓	✓	✓	✓	-	✓	-	✓	-	
Sharma <i>et al.</i> , 1995	✓	✓	-	✓	✓	-	✓	✓	-	
Sithipong <i>et al.</i> , 1985	✓	-	-	✓	-	✓	-	-	-	
Soponronnarit & Assayo, 1991	✓	✓	✓	✓	✓	✓	✓	-	-	Drying system efficiency
Soponronnarit <i>et al.</i> , 1991	✓	✓	✓	✓	✓	✓	✓	-	-	Specific energy consumption

Source: (Leon *et al.* 2002)

Appendix 7: Batch size of beef drying

Generally in Bhutan, longer lengths of the strips are preferred. The width and thickness of the strips are approximately 1 and 3 cm respectively. However FAO (1990) recommended a strip length of 20 – 70 cm for effective drying. Thus the length of the beef strips is assumed as 60 cm, equal to the depth of the dryer trough. The total quantity of beef that could be dried per batch is calculated in the following paragraphs.

$$\text{Volume of each strip} = 0.6 \times 0.01 \times 0.03 = 0.00018 \text{ m}^3$$

Assuming the gap between strips as 1 cm for air flow and to avoid contact with each other which otherwise would result in non-uniform drying of the surface in contact with the other strip.

$$\text{No. of strips in row} = \frac{\text{length of dryer cabinet}}{(\text{width of beef strip} + \text{gap between strips})} = \frac{2.2}{(0.03 + 0.01)} = 55$$

Also, there has to be gap between the rows of beef for loading and unloading of beef strips and to avoid contact with each other. The gap between rows is assumed as 10 cm.

$$\text{No. of rows} = \frac{\text{width of dryer cabinet}}{\text{gap between rows}} = \frac{1.25}{0.1} = 12$$

$$\text{Total volume of beef per batch} = 0.00018 \times 55 \times 12 = 0.1188 \text{ m}^3$$

$$\begin{aligned} \text{Quantity of beef per batch} &= \text{total volume per batch} \times \text{density of beef} \\ &= 0.1188 \times 1000 = 119 \text{ kg} \end{aligned}$$

Thus the quantity of beef that could be dried per batch is approximately 119 kg. However, the batch size has to be verified as to whether the same air flow rate i.e. 3120 kg/hr used for chilli can remove the moisture from beef within the stipulated time.

As suggested by Fuller and Lu Aye (2002), this can be done by making two assumptions. The first assumption is the average pick-up efficiency through the drying period, which according to Brenndorfer *et al.* (1985 in Fuller & Lu Aye 2002) is

approximately 30% for a well designed dryer system. The second assumption is dryer exhaust air relative humidity which is assumed as 40% as suggested by Dahlenburg (1975 in Fuller & Lu Aye 2002). Using these two assumptions and referring to the psychrometric chart in Fig. A.1, the quantity of moisture that can be removed by the drying air at 60°C and 3120 kg/hr is calculated as shown below.

$$\begin{aligned}
 \text{Relative humidity of ambient air} &= 70\% \\
 \text{Average ambient air temp.} &= 15^\circ \text{C} \\
 \text{Humidity ratio of ambient air, } W_i &= 7 \text{ gm/kg} \\
 \text{Humidity ratio of exhaust drying air, } W_o &= 18 \text{ gm/kg (from psychrometric chart)} \\
 \left(\begin{array}{c} \text{Moisture removal capacity} \\ \text{of drying air per hour} \end{array} \right) &= \left(\frac{W_o - W_i}{1000} \right) \times \text{air flow rate} \times \text{pick-up efficiency} \\
 &= \left(\frac{18 - 7}{1000} \right) \times 3120 \times 0.3 = 10.3 \text{ kg/hr}
 \end{aligned}$$

Assuming drying time of beef as 8 hours from Section 3.4.2,

$$\begin{aligned}
 \left(\begin{array}{c} \text{Moisture} \\ \text{evaporated} \\ \text{per hour} \end{array} \right) &= \frac{\left(\begin{array}{c} \text{Weight of} \\ \text{wet sample} \end{array} \right) \times \left[\left(\begin{array}{c} \text{Initial moisture} \\ \text{content of product} \end{array} \right) - \left(\begin{array}{c} \text{Final moisture content} \\ \text{of product} \end{array} \right) \right]}{(100 - \text{Final moisture content of product}) \times \text{Duration of drying time}} \\
 &= \frac{119 \times (80 - 10)}{(100 - 10) \times 8} = 11.6 \text{ kg/hr}
 \end{aligned}$$

However, the design air flow rate of 3120 kg/hr can remove only 10.3 kg of moisture per hour. This is less than the moisture evaporation rate of the above batch size.

Therefore, the batch size has to be reduced to 100 kg. At this batch size, the moisture evaporation rate is 9.7 kg/hr which is less than the moisture removal capacity of the dryer air flow rate. Hence the batch size for beef is fixed at 100 kg/batch.

ASHRAE PSYCHROMETRIC CHART NO. 3
HIGH TEMPERATURE 10°C to 120°C SEA LEVEL
BAROMETRIC PRESSURE 101.325 kPa

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Fig. A.1. Psychrometric chart

Source: (ASHRAE 2001)

The humidity ratio of ambient air is 7 gm/kg of dry air (point D) while it is 18 gm/kg of dry air (point E) for air outlet from the dryer.

Appendix 8: TRNSYS components

The TRNSYS components used in this study are briefly explained in the following sections. The individual TRNSYS components are connected and they form a flowchart of information from one component to another. Fig. A.2 shows the information flow diagram. The information flow diagram shows the manner in which all the system components are interconnected. The arrow heads show the direction of flow of information.

i. Weather data generator: Type 54

As explained in Section 4.2, this component generates hourly weather data with average monthly solar radiation, dry bulb temperature, humidity ratio and wind speed as inputs. The data file generated is similar to a Typical Meteorological Year data file.

ii. Solar radiation processor: Type 16

As the weather generator generates horizontal surface radiation over an hourly interval, the solar radiation processor is used to calculate the solar radiation at a different orientation, i.e. that of the collector. This subroutine also can interpolate the data over different time intervals if required.

iii. Solar collector: Type 1

The thermal performance of the flat plate solar collector is modeled using a Type 1 solar collector. This subroutine converts the solar radiation falling on the absorber plate into heat by taking into account the mass flow rate, specific heat and the inlet temperature of air. Also this subroutine computes the temperature rise of the air flowing through the collector and the total energy gained by the collector.

iv. Fan: Type 3

Since the dryer in this study is a forced convective type, a fan is used to circulate the drying air. The fan requires an external energy source i.e. electricity to drive it.

v. Auxiliary heaters: Type 6

As the dryer in this study is intended to be used during different times of the year and day, a supplementary energy source is necessary to increase the air temperature during the times of no or low solar radiation. This component computes the total supplementary energy required by the dryer at these times, including the losses. However, this subroutine does not take into account the energy used for driving fan.

Fig. A.2. Information flow diagram in TRNSYS model

vi. Pipe duct: Type 31-1 and Type 31-2

This component is used to model the air ducts used in the system. Both the ducts before and after the auxiliary heater are represented by this component. This component calculates the energy losses occurring in the air ducts.

vii. Forcing function: Type 14-1

This component is used to control the operation of the auxiliary heater. The instantaneous output of this component is connected as a control signal of the auxiliary heater. This component will only turn the auxiliary heater on when the dryer is loaded and there is either low or no solar radiation.

viii. Forcing function-1: Type 14-2 in conjunction with Equa-2

These two components are used to model the operating cycle of the dryer. For example, during the months of August and September, these two components will simulate starting the dryer at 10 a.m and turning the dryer off at set time. This loading cycle will be repeated everyday during the months of August and September. The outputs of the equation are connected as inputs to the dryer.

ix. Psychrometrics: Type 33 d & e

Two psychrometric subroutines are used to compute the parameters such as wet bulb temperature, relative humidity and specific humidity of the drying air. These parameters are used as inputs to the dryer.

x. Quantity integrator: Type 24 in conjunction with Equa-1

These components are used to compute the total useful energy gain by the solar collector, total auxiliary energy required and solar fraction of the drying system. The solar fraction is calculated using Equation A.1 (Duffie & Beckman 1991)

$$SF = \frac{Q_{si}}{Q_{si} + Q_{ai}} \quad (A.1)$$

where SF = solar fraction

Q_{ai} = energy required by auxiliary heater (kJ)

Q_{si} = energy gained by solar energy system (kJ)

Appendix 9: Source code for Type 104 TRNSYS component

```

SUBROUTINE TYPE104(time,xin,out,t,dt,dt,par,info,icntrl,*)

c THIS SUBROUTINE MODELS A THIN LAYER DRYING BED USING PAGE'S THIN
c LAYER DRYING EQUATION FOR THROUGH FLOW.
c
c DEFINITION OF VARIABLES USED IN THIS MODEL
c
c Ab   = AREA OF DRYING BED (m2)
c dk   = Drying constant
c Es   = SUPPLEMENTARY ENERGY REQUIRED (kJ/hr)
c fmc  = MOISTURE CONTENT AT THE END OF TIME STEP (% db)
c fmcw = MOISTURE CONTENT AT THE END OF TIME STEP (% wb)
c hrin = HUMIDITY RATIO OF INPUT AIR
c Ir   = Horizontal surface radiation (kJ/m2)
c MCs  = MOISTURE CONTENT AT START (% wb)
c Mi   = INITIAL MOISTURE CONTENT OF CROP (%wb)
c Midb = INITIAL MOISTURE CONTENT OF CROP (% db)
c Mw   = WEIGHT OF WATER EVAPORATED (kg)
c Mw1  = MASS OF WATER IN CROP AT START OF TIME (kg)
c Mw2  = MASS OF WATER IN CROP AT END OF TIME STEP (kg)
c Pb   = ENERGY CONSUMED BY BLOWER (kJ/hr)
c Pws  = SATURATED PRESSURE OF WATER VAPOUR (Pa)
c rh   = RELATIVE HUMIDITY (%)
c tm   = DRYING TIME (MINUTES)
c tc   = TEMPERATURE OF CROP (deg C)
c tcwb = TEMPERATURE OF DRYER AT WET BULB (deg C)
c td   = TEMPERATURE OF DRYER (deg C)
c Tin  = INITIAL TEMPERATURE OF DRYING AIR (deg C)
c Tout = OUTLET TEMPERATURE OF COLLECTOR (deg C)
c ts   = DRYING START TIME
c u    = PAGE EQUATION CONSTANT
c va   = DRYING AIR VELOCITY (m/s)
c W    = WEIGHT OF WET SAMPLE CROP (kg)
c Wd   = WEIGHT OF DRY SAMPLE (kg)
c
c      DOUBLE PRECISION xin,out
c      INTEGER info
c      REAL t,dt,dt,par
c      CHARACTER*3 ycheck(15),ocheck(9)
c      DIMENSION xin(20),out(20),par(5),info(10), dt,dt(1), t(1)
c      if (info(7) .ge. 0.0 ) go to 10
c
c START SIMULATION
c      info(6) = 9
c      call typeck (1,info,15,1,0)
c      call rcheck(info,ycheck,ocheck)
c
10    continue
c
c DEFINING THE PARAMETERS USED IN THIS MODEL
c      Ab = par(1)
c
c DEFINING THE INPUTS USED IN THIS MODEL
c      td = xin(1)
c      rh = xin(2)
c      va = xin(3)
c      MCs = xin(4)
c      hrin = xin(5)
c      tcwb = xin(6)
c      Pb = xin(7)
c      W = xin(8)

```

```

      Mi = xin(9)
      ts = xin(10)
      Es = xin(11)
      dk = xin(12)
      Tout = xin(13)
      Tin = xin(14)
      Ir = xin(15)

c
      if (ts .eq. time) MCs = Mi
      if (info(7) .gt. 0.0) go to 944
      mcsw = MCs
944  continue
c
c CONVERT %WB MOISTURE CONTENT TO %DB
      Midb = ((1./(1.-(mcsw/100.)))-1.)*100.
c
c CALCULATE WEIGHT OF DRY CROP
      Ws = Mi/100. * W
      Wd = W - Ws
c
c CALCULATE MASS OF WATER IN THE CROP AT STARTING OF TIME STEP
      Mw1 = (mcsw/100. * Wd)/(1. - mcsw/100.)
c
c LET CROP TEMPERATURE IS EQUAL TO DRYER TEMPERATURE
      tc = td
c
c CONVERT TEMPERATURE TO ABSOLUTE VALUE
      tck = tc + 273.15
c
c CONVERT RELATIVE HUMIDITY TO DECIMAL
      rh = rh/100.
c
c DRYING RATE EQUATION COMPUTATION (using kalimullah model, Equation 5.2 in
Section 5.6.2)
      equimc = ((alog((rh-0.8406)/(-0.8189)))/(-0.000739*tc))
      &**(1./1.4102)
c
c COMPUTE FINAL MOISTURE CONTENT (Equation 5.1 in Section 5.6.1)
      mois=Midb-equimc
      esp=exp((-dk)*(time-ts))
      fmc =(esp*mois)+equimc
c CONVERT FINAL MOISTURE CONTENT (db) TO (wb)
      fmcw = 1.-(1./(1. + (fmc/100.)))
c
c MASS OF WATER REMOVED AT THE END OF TIME STEP
      Mw2 = (fmcw * Wd)/(1. - fmcw)
c
c MASS OF WATER REMOVED DURING THE TIME PERIOD
      wloss = Mw1 - Mw2
c
c COMPUTE DENSITY OF MOIST INLET AIR (ASHRAE 2001)
      dair = ((101325./tck)/286.9) * ((1. + hrin)/(1. + 1.608 * hrin))
c
c COMPUTE AIR FLOW RATE THROUGH BED
      airmass = va * Ab * 3600. * dair
c COMPUTE SPECIFIC HUMIDITY OF AIR
      sph_oair = hrin + (wloss/(3120))
c
c COMPUTE SATURATION PRESSURE OF AIR AT WET BULB TEMP
      sat_preair = (exp(77.3450 + (0.0057 * (273.15 + tcwb))
&- (7235./(273.15 + tcwb))))/((273.15 + tcwb)**8.2)
c
c COMPUTE SPECIFIC HUMIDITY OF SATURATED AIR Wark and Richards 1999 p.553)
      wsat = (0.622 * sat_preair)/(101325. - sat_preair)
c

```

```

c COMPUTE COLLECTOR EFFICIENCY (using Equation 5.3 in Section 5.6.3)
  coll = 3120.*1.02*(Tout-Tin)/73./Ir
  coll = coll*100.
c
c COMPUTE SYSTEM EFFICIENCY (using Equation 5.4 in Section 5.6.3)
  syseff = wloss * 2750. / ((Ir*73.)+ Pb + Es)
  syseff = syseff * 100.
c
c COMPUTE PICKUP EFFICIENCY (using Equation 5.5 in Section 5.6.3)
  pickup = ((sph_oair - hrin)/(wsat - hrin))
  pickup = pickup * 100.
c
c LIMIT DRYING TO 10% FINAL MOISTURE CONTENT (wb)
  if (fmcw < 0.1) then
    return 1
  else
c
c COMPUTE DRYING TIME (hours)
    tm=time-ts
c
c CONVERT FINAL MOISTURE CONTENT TO %
    fmcw = fmcw * 100.
c
c SETTING THE OUTPUTS
    out(1) = td
    out(2) = tm
    out(3) = syseff
    out(4) = coll
    out(5) = fmcw
    out(6) = Pb
    out(7) = fmc
    out(8) = equimc
    out(9) = pickup
    end if
  return 1
end

```

Appendix 10: Estimation of real discount rate

The discount rate is a factor by which the future sum of money is converted to present value. This is of two different rates. The first one is nominal discount rate, which does not take into account the inflation rate of a country. The other is real discount rate which takes into account the inflation rate of a country. The real discount rate can be calculated by the Equation A.2.

$$i_r = \frac{(i_{nominal} - i)}{(1 + i)} \quad (A.2)$$

Where, i_r = real discount rate
 $i_{nominal}$ = nominal discount rate
 i = inflation rate

The inflation rate of a country is the change in the price over a certain time period. The inflation rate is calculated from the consumer price index of a country over the given period of a time by the Equation A.3 (Taggart *et al.* 1996 p.520).

$$Inflation\ rate = \frac{(Current\ year's\ price\ level - Last\ year's\ price\ level)}{(Last\ year's\ price\ level)} \times 100 \quad (A.3)$$

The inflation rate for nine years based on the consumer price index was calculated. The inflation rate was then used to calculate the real discount rate of Bhutan. Further, a 13% interest rate was used based on the present lending rate of the banks in Bhutan. From Table 1, Bhutan's real discount rate varies from 6% to 13%. So, in this study a real discount rate of 13% was adopted based on year 2004.

Table A.1: Consumer price index and real discount rate

Year	Month	Consumer price index (%)	Half-yearly inflation (%)	Real discount rate (%)
1995	June	413.2	-	-
	Dec	437.7	5.93	6.67
1996	June	451.7	3.20	9.50
	Dec	474.1	4.96	7.66
1997	June	484.9	2.28	10.48
	Dec	501.2	3.36	9.33
1998	June	528.7	5.49	7.12
	Dec	561.7	6.24	6.36
1999	June	577.3	2.78	9.95
	Dec	587.0	1.68	11.13
2000	June	598.1	1.89	10.90
	Dec	612.9	2.47	10.27
2001	June	619.5	1.08	11.80
	Dec	632.8	2.15	10.63
2002	June	636.1	0.52	12.41
	Dec	647.2	1.75	11.06
2003	June	647.8	0.09	12.90
	Dec	655.7	1.22	11.64
2004	June	655.9	0.03	12.97

* Based on 1979 base year, i.e December 1979 = 100 %

Nominal interest rate: 13%

Source: (RMA 2001, 2003, 2004)

Appendix 11: Detailed cost estimate of the solar dryer system

Particulars	Unit	Rate (Nu)	Qty.	Amount (Nu)	Amount (US \$)	Percentage of total cost
1 Land clearing						
Clearing jungle including uprooting of vegetation	m ²	4.21	100.00	421.00	9.27	0.40
Providing and laying cement, concrete 1:5:10; 50 mm aggregates in plinth	m ³	1 490.00	3.65	5 438.50	119.79	5.11
Sub total				6 738.43	148.42	6.34
2 Solar collector and accessories						
CGI sheet, 24 g (0.63 mm)	tonne	32 038.00	0.36	11 565.72	254.75	10.87
Timber, mixed conifer	m ³	2 825.00	1.20	3 390.00	74.67	3.19
Plywood, 4mm thick, commercial ply	m ²	97.00	73.00	7 081.00	155.97	6.66
Plain glass, 3 mm thick	m ²	210.00	73.00	15 330.00	337.67	14.41
Black paint	litre	82.00	20.00	1 640.00	36.12	1.54
Putty (for sealing gaps)	kg	20.00	20.00	400.00	8.81	0.38
Saw dust	kg	1.00	1 600.00	1 600.00	35.24	1.50
Sub total				47 157.73	1 038.72	44.33
3 Dryer trough and frame						
Steel sheet (250 Mpa), 3.5 mm thick	kg	24.00	157.00	3 768.00	83.00	3.54
Timber, mixed conifer	m ³	2 825.00	0.50	1 412.50	31.11	1.33
Wire gauze, 0.85 mm aperture	m ²	86.20	3.00	258.60	5.70	0.24
Sub total				6 254.97	137.77	5.88

	Particulars	Unit	Rate (Nu)	Qty.	Amount (Nu)	Amount (US \$)	Percentage of total cost
4	Duct heater, blower and ducts						
	Duct heater	No	21 562.50	1.00	21 562.50	474.94	20.27
	Blower, 2 kW, 220 V, 10 A, 50 Hz	No	14 400.00	1.00	14 400.00	317.18	13.54
	Plain GI sheet, 24g (for ducts)	tonne	32 560.00	0.03	1 123.32	24.74	1.06
	Sub total				37 085.82	816.87	34.87
5	Miscellaneous items						
	Nails, bolts, nuts and screws	kg	32.00	2.00	64.00	1.41	0.06
	Sub total				73.60	1.62	0.07
6	Installation and labour cost (10% of sum of 2 - 5)				9 057.21	199.50	8.51
	Subtotal				9 057.21	199.50	8.51
7	Grand total				106 367.75	2 342.90	

Appendix 12: Exchange rate, US Dollar to Ngultrum

Period	1999	2000	2001	2002	2003	2004
January	42.51	43.55	46.54	48.34	47.93	45.46
February	42.46	43.61	46.52	48.69	47.74	45.27
March	42.44	43.59	46.62	48.74	47.65	45.02
April	42.73	43.64	46.79	48.92	47.38	43.93
May	42.77	43.97	46.98	49.00	47.08	45.25
June	43.14	44.69	47.01	48.96	46.72	45.51
July	43.29	44.78	47.13	48.76	46.23	-
August	43.46	45.69	47.13	48.59	45.94	-
September	43.54	45.89	47.65	48.44	45.85	-
October	43.45	46.35	48.02	48.37	45.39	-
November	43.40	46.78	48.00	48.38	45.47	-
December	43.30	46.75	47.92	48.14	45.59	-
Average	43.04	44.94	47.13	48.61	46.58	45.07

Source: (RMA 2004)

Appendix 13: Cost-benefit analysis of chilli only

	Parameters	Unit	Amount (US \$)
1	Parameters		
	Capacity of dryer to dry chilli	tonne/year	4.50
	Price of fresh chilli ^a	US \$/kg	0.98
	Price of dried chilli ^b	US \$/kg	4.91
2	Capital cost		
	Total investment cost	US \$	2 342.90
3	Operating cost		
	Total supplementary energy cost	US \$/year	453.44
	Operators salary	US \$/year	86.96
	Cost of fresh chilli	US \$/year	4 402.17
	Sub total		4 942.57
4	Benefits		
	Revenue from sale of dried chilli	US \$/year	3 682.26
5	Discounted cash flow analysis		
	Residual value	US \$	468.58
	Discount rate	decimal	0.13
	Project life	years	15.00
	Discounted revenue	US \$	23 796.15
	Discounted residual value	US \$	74.92
	Discounted O & M cost	US \$	31 940.76
	Total discounted benefit	US \$	23 871.07
	Total discounted costs	US \$	34 283.66
	Net present value	US \$	-10 412.60
	Benefit cost ratio		0.70
	Internal rate of return	%	-
	Discounted pay backperiod	year	-

Source: ^a - (MoA 2004b)

^b - (MoA 2004a)

Appendix 14: Cost-benefit analysis of chilli & beef combined

	Parameters	Unit	Amount (US \$)
1	Parameters		
	Capacity of dryer to dry chilli	tonne/year	4.50
	Capacity of dryer to dry beef	tonne/year	24.40
	Price of fresh chilli	US \$/kg	0.98
	Price of dried chilli	US \$/kg	4.91
	Price of fresh beef ^c	US \$/kg	1.14
	Price of dried beef ^d	US \$/kg	5.43
2	Capital cost		
	Total investment cost	US \$	2 342.90
3	Operating cost		
	Total supplementary energy cost	US \$/year	2 205.64
	Operators salary	US \$/year	521.74
	Cost of fresh chilli	US \$/year	4 402.17
	Cost of fresh beef	US \$/year	27 847.83
	Sub total		34 977.38
4	Benefits		
	Revenue from sale of dried chilli	US \$/year	3 682.26
	Revenue from sale of dried beef	US \$/year	29 439.13
5	Discounted cash flow analysis		
	Residual value	US \$	468.58
	Discount rate	decimal	0.13
	Project life	years	15.00
	Discounted revenue	US \$	214 042.96
	Discounted residual value	US \$	74.92
	Discounted O & M cost	US \$	226 037.07
	Total discounted benefit	US \$	214 117.88
	Total discounted costs	US \$	228 379.98
	Net present value	US \$	-14 262.09
	Benefit cost ratio		0.94
	Internal rate of return	%	-
	Discounted pay backperiod	year	-

Source: ^c - (MoA 2004b)

^d - (Wangmo 2004)

Appendix 15: Optimisation of collector area

Area (m ²)	Fixed cost (US\$)	Variable cost (US \$)	Maintenance cost (US \$)	Salvage value (US \$)	Supplementary energy cost		Total annual cost (US \$)
					chilli (US \$)	Beef (US \$)	
0	1 174.34	0.00	27.54	112.70	588.86	2 145.67	2 894.07
10	1 174.34	161.60	31.33	128.21	564.42	2 057.40	2 803.32
20	1 174.34	323.20	35.12	143.72	540.36	1 988.14	2 731.95
30	1 174.34	484.81	38.91	159.23	519.18	1 943.47	2 688.06
40	1 174.34	646.41	42.70	174.74	500.23	1 893.03	2 640.62
50	1 174.34	808.01	46.49	190.25	484.12	1 844.55	2 597.98
60	1 174.34	969.61	50.28	205.76	469.67	1 800.60	2 561.54
70	1 174.34	1 131.21	54.07	221.27	456.95	1 762.20	2 532.37
80	1 174.34	1 292.82	57.86	236.77	445.76	1 727.56	2 508.50
90	1 174.34	1 454.42	61.65	252.28	435.90	1 694.44	2 487.47
100	1 174.34	1 616.02	65.44	267.79	427.22	1 664.45	2 470.76
110	1 174.34	1 777.62	69.23	283.30	419.59	1 638.04	2 458.67
120	1 174.34	1 939.22	73.02	298.81	412.86	1 615.72	2 451.58
130	1 174.34	2 100.82	76.81	314.32	406.94	1 595.25	2 447.14
140	1 174.34	2 262.43	80.60	329.83	401.73	1 577.23	2 445.87
150	1 174.34	2 424.03	84.39	345.34	397.17	1 561.36	2 447.39
160	1 174.34	2 585.63	88.18	360.85	393.17	1 547.39	2 451.38
170	1 174.34	2 747.23	91.97	376.36	389.65	1 535.12	2 457.54
180	1 174.34	2 908.83	95.76	391.86	386.55	1 524.29	2 465.56
190	1 174.34	3 070.44	99.55	407.37	383.85	1 514.76	2 475.29
200	1 174.34	3 232.04	103.34	422.88	381.47	1 506.38	2 486.48

Appendix 16: Cost-benefit analysis of optimised system

Parameters	Unit	Amount (US \$)	
		Solar system	Electrical heating system
1 Parameters			
Capacity of dryer to dry chilli	tonne/year	4.50	4.50
Capacity of dryer to dry beef	tonne/year	24.40	24.40
Price of fresh chilli	US \$/kg	0.98	0.98
Price of dried chilli	US \$/kg	4.91	4.91
Price of fresh beef	US \$/kg	1.14	1.14
Price of dried beef	US \$/kg	5.43	5.43
2 Capital cost			
Total investment cost	US \$	3 436.77	1 174.34
3 Operating cost			
Total supplementary energy cost	US \$/year	1 978.96	2 734.53
Operators salary	US \$/year	521.74	521.74
Cost of fresh chilli	US \$/year	4 402.17	4 402.17
Cost of fresh beef	US \$/year	27 847.83	27 847.83
Sub total		34 750.70	35 506.27
4 Benefits			
Revenue from sale of dried chilli	US \$/year	3 682.26	3 682.26
Revenue from sale of dried beef	US \$/year	29 439.13	29 439.13
5 Discounted cash flow analysis			
Residual value	US \$	687.35	234.87
Discount rate	decimal	0.13	0.13
Project life	years	15.00	15.00
Discounted revenue	US \$	214 042.96	214 042.96
Discounted residual value	US \$	109.90	37.55
Discounted O & M cost	US \$	224 572.18	229 454.96
Total discounted benefit	US \$	214 152.86	214 080.51
Total discounted costs	US \$	228 008.95	230 629.30
Net present value	US \$	-13 856.09	-16 548.79
Benefit cost ratio		0.94	0.93
Internal rate of return	%	-	-
Discounted pay backperiod	year	-	-

APPENDIX 17: Source code of Type 104 TRNSYS component in CD

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