Solar drying and CO2 emissions mitigation: potential for selected cash crops in India

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Abstract

An attempt to estimate the potential of solar crop drying for some selected cash crops in India has been made. The amount of cash crops that can be dried by solar dryers and the required aperture area of solar dryers have been estimated. Estimates for unit cost of solar drying for different crops have also been worked out. The potential of net fossil CO2 emissions mitigation due to the amounts of different fuels that would be saved by solar drying has been estimated along with the unit cost of CO2 emissions mitigation.

Keywords: Solar crop drying; Cash crops; Potential estimation; CO_2 emissions

1. Introduction

Solar drying is a potential decentralized thermal application of solar energy particularly in developing countries (Ekcchukwu and Norton, 1999; Garg and Prakash, 2000; Sodha et al., 1987). However, so far, there has been very little field penetration of solar drying technology. In the initial phase of dissemination, identification of suitable niche areas for using solar dryers would be extremely helpful towards their market penetration. In this context, one of the possible areas of immediate intervention in developing countries appears to be the solar drying of cash crops such as tobacco, tea, coffee, grapes raisin, small cardamom, chilli, coriander seeds, ginger, turmeric, black pepper, onion flakes, and garlic flakes etc. For such crops, even with the capital intensive nature of solar dryers, the unit cost of solar drying is expected to be a small fraction of the selling price of the dried product. In this paper, an attempt has made towards potential assessment of solar drying of some cash crops in India. The resulting net mitigation of CO_2 emissions due to realization of the estimated potential of solar drying of the selected cash crops has also been estimated.

2. Methodology

2.1. Estimation of potential amounts of cash crops

The initial estimate for the potential amount (Q_{dry}) of a cash crop for solar drying can essentially begin with the gross annual production (Q_{tot}) of the crop in the country. However, in areas with inadequate solar

Nomenclature

A_a	aperture area of solar dryer (m^2)
$BE_{CUF,i}$	break-even value of capacity utilization factor (fraction)
$BE_{pc,i}$	break-even value of cost of solar dryer per unit aperture area (Rs/m^2)
$BE_{pf,i}$	break-even value of price of ith fuel
C_a	net annual cost of the solar dryer (Rs)
CEF_i	carbon emission factor of ith fuel
$CRF_{d,T}$	capital recovery factor
CUF	capacity utilization factor of solar dryer
d	discount rate in fraction
EM	CO_2 emissions embodied in the solar dryer (kg/m^2)
FCO_i	fraction of carbon oxidized during combustion of ith fuel
f_{es}	fraction of useful energy requirement for drying supplemented by solar energy
f_i	fraction of crop currently being dried by ith fuel
f_{pp}	correction factor for the purchasing power of the user
f	fraction of crop used in raw form
f_{sol}	correction factor for solar radiation availability
GE_c	potential of mitigating gross fossil CO_2 emissions (kg)
h_{fg}	enthalpy of evaporation of water at the drying temperature (MJ/kg)
m	annual operation and maintenance cost of solar dryer as a fraction of its capital cost
M_f	final moisture content of the crop on wet basis (fraction)
M_i	initial moisture content of the crop on wet basis (fraction)
NE_c	net annual potential of CO_2 emissions mitigation (kg)
p_c	cost of the solar dryer per unit aperture area (Rs/m^2)
Q_{dry}	potential amount of a cash crop for solar drying (kg)
Q_{tot}	gross annual crop production (kg)
s	specific heat of raw crop (MJ/kg/°C)
T	useful life time of the solar dryer (years)
T_a	ambient temperature (°C)
T_d	drying temperature (°C)
UC_{dry}	unit cost of solar crop drying (Rs/kg)
UC_{mit}	unit cost of fossil CO_2 emissions mitigation (Rs/kg)
W_r	amount of water to be removed per unit amount of dried crop (kg)
r\&	thermal efficiency of the solar dryer
gi	efficiency of utilization of ith fuel in a conventional dryer

radiation availability solar dryers cannot be used. Similarly, all the producers of the crop perhaps cannot afford to invest in a solar dryer. Moreover, a certain fraction of the total production of certain crops is used in raw form itself. Therefore, a realistic estimate for the potential amount of cash crop available for solar drying can be obtained form the gross annual production modified by correction factors for (i) the fraction of crop used in raw form (f_r), (ii) purchasing power of the user (f_{pp}) and (iii) solar radiation availability (f_{sol}).

$$Q_{dry} = Q_{tot}(1 - f_r) f_{pp} f_{sol} \quad (1)$$

2.2. Estimation of required aperture area of solar dryers

The amount of water to be removed (W_r) per unit amount of dried crop can be calculated as

$$W_r = \frac{M_i - M_f}{1 - M_i} \quad (2)$$

where M_i and M_f are initial and final moisture contents (in fraction) of the crop on wet basis.

The useful energy required for drying unit amount (on dry mass basis) of a crop can be estimated using the following relation

$$UE_{dry} = \left(\frac{1-M_f}{1-M_i}\right)s(T_d - T_a) + \left(\frac{M_i - M_f}{1 - M_i}\right)h_{fg} \quad (3)$$

In Eq. (3) the first term on the right hand side represents the useful energy required for sensible heating (of an amount of wet crop required to produce unit amount of dried crop) of wet crop from the ambient temperature (T_a) to the drying temperature (T_d). The second term represents the useful energy required (per unit amount of dried crop) for evaporation of moisture in the crop with h_{fg} representing the enthalpy of evaporation of water at the drying temperature. The specific heat, *s*, of the wet crop can be estimated (in MJ/kg/°C) from Siebel's formula (ASHRAE, 1974)

$$s = (0.80M_i + 0.20)4.1868 \times 10^{-3} \quad \mathbf{(4)}$$

A solar drying system may be designed to meet the entire useful energy requirement for drying (UE_{dry}) or a certain fraction (f_{es}) of the same. The aperture area of solar dryer (A_a) required for drying Q_{dry} amount of a crop (on dry basis) can be estimated as

$$A_a = \left(\frac{f_{es} Q_{dry} UF_{dry}}{365 I\, CUF \eta_d}\right) \quad (5)$$

where I represents the design value of daily solar radiation, η_d the thermal efficiency of the solar dryer and CUF the capacity utilization factor of solar dryer. The capacity utilization factor of a solar dryer depends upon (i) the number of days in a year solar dryer is used for drying, and (ii) the amount of dried crop per batch as a fraction of its rated capacity. The cash crops considered in this study being perishable, it is assumed that the same need to be dried within the harvesting season of the respective crop. Therefore, unless a dryer is designed for drying multiple crops, its capacity utilization factor is essentially decided by the length of harvesting season (i.e. if the solar dryer is loaded fully in each batch of drying, the CUF is simply equal to the harvesting season expressed as a fraction of the total number of days in a year).

2.3. Unit cost of solar drying

The unit cost of solar crop drying (UC_{dry}) is essentially the ratio of total annualized cost of the solar dryer to the annual amount of the crop dried by the solar dryer. It can be mathematically expressed as (Kandpal and Garg, 2003)

$$UC_{dry} = \frac{f_{es} UE_{dry} p_c (CRF_{d,T} + m)}{365 CUF I \eta_d} \quad (6)$$

where p_c represents the cost of the solar dryer per unit aperture area and *m* the annual operation and maintenance cost of solar dryer as a fraction of its capital cost. $CRF_{d,T}$ represents the capital recovery factor and it is defined as

$$CRF_{d,T} = \frac{d(1+d)^T}{(1+d)^T - 1} \quad \mathbf{(7)}$$

for discount rate *d* and useful life time *T* of the solar dryer. It may be noted that the possibility of economy of scale in the capital cost of solar dryer has not been considered in Eq. (6). Eqs. (3), (5) and (6) are derived for dry mass basis of the crop. The same can also be expressed on wet mass basis as presented in Appendix A of this paper.

2.4. Mitigation of fossil CO2 emissions

As the fuel mix replaced by the use of solar dryer(s) may be different for each crop, a crop wise estimation of net fossil CO_2 emissions mitigation potential is essential for this purpose. For each crop, the total useful energy provided by the solar dryer is estimated along with its desegregation for each fossil fuel replaced by solar drying. Based on the efficiencies (η_i) of the utilization of different fuels for drying, their respective carbon emission factors (CEF_i) and the fraction of carbon oxidized during combustion (FCO_i) it is possible to estimate the potential of mitigating gross fossil CO_2 emissions (GE_c) by the use of solar dryers through the following expression as

$$GE_c = \sum_i f_i \left(\frac{f_{es} Q_{dry} UE_d}{\eta_i}\right) CEF_i FCO_i \left(\frac{44}{12}\right) \quad \mathbf{(8)}$$

where *f* represents the fraction of crop currently being dried by ith fuel.

The following expression for the net annual mitigation in CO_2 emissions (NE_c) can be obtained by subtracting the annualized CO_2 emissions embodied in the solar dryer from the gross annual CO_2 emissions mitigation potential

$$NE_c = \left\{\sum_i f_i \left(\frac{f_{es} Q_{dry} UE_{dry}}{\eta_i}\right) CEF_i FCO_i \frac{44}{12}\right\} - \left(\frac{EM\, A_a}{T}\right) \quad (9)$$

where EM represents CO_2 emissions embodied in the solar dryer per unit aperture area. In Eq. (9) it is assumed that the dryers used for all the crops are identical with the same value of embodied CO_2 emissions per square meter of aperture area.

It may be noted that some of the cash crops considered in this study are predominantly sun dried at present. The use of solar dryers in such cases may not result in any CO_2 emissions mitigation. It is also assumed in this study that all the carbon oxidized during combustion of different fuels is converted to CO_2 only.

As mentioned earlier, so far, the solar dryers have found very little acceptance at the field level. Similar situation is likely to prevail for another decade or so. Therefore, in order to estimate the likely potential for the next ten years it is assumed that dissemination of the solar dryers would, at the best, follow a compound growth curve. The available indicative data on the past dissemination of solar dryers was used for future projection of their dissemination and also for estimation of the corresponding net fossil CO_2 emissions mitigation potential.

2.5. Unit cost of fossil CO2 emissions mitigation

The unit cost of fossil CO2 emissions mitigation is essentially the ratio of net annual cost of solar dryer to the net annual fossil CO_2 emissions mitigated by its use. The net annual cost of solar dryer is the difference between the annualized cost of purchase, installation, operation and maintenance of the solar dryer and the monetary worth of the fuels saved/substituted by the use of solar dryer for a period of one year. If the use of the solar dryer substitutes more than one fuel then the total monetary worth of fuels saved by using the solar dryer for a period of one year would depend upon the fuel mix saved and the respective costs of the fuels to the user. The net annual cost (C_a) of the solar dryer can be estimated as

$$C_a = A_a\left\{p_c(CRF_{d,T}+m) - \sum_i f_i\left(\frac{365/CUFf,\wedge_i}{\eta_i}\right)\right\} \quad (10)$$

where $p_{f,i}$ represents the market price of ith fuel.

The unit cost of fossil CO2 emissions mitigation (UC_{mit}) can therefore be expressed as

$$UC_{mit} = \frac{A_a\left\{p_c(CRF_{d)T}+m) - \sum_i f_i\left(\frac{365ICUF_{gd}p_{f,i}}{\wedge}\right)\right\}}{\left\{\sum_i f_i\left(\frac{f_{es}Q_{dry}UE_{dry}}{\eta_i}\right) yCEF_iFCO_i441 - \left(\frac{EMA_c}{T}\right)\right.} \quad (11)$$

Since the amount of CO_2 emissions mitigated resulting from the use of a solar dryer for drying a crop would depend upon the fuel(s) substituted by the solar dryer, the cost of CO2 emissions mitigation may be different for the replacement of different fuels. The unit cost of CO2 emissions mitigation for each fuel can be estimated by substituting the value *off* equal to unity in Eq. (11) for each fuel.

In certain cases the annual monetary benefit accrued to the user due to fuel saving from the use of a solar dryer may be higher than the total of annualized capital cost of the dryer and the cost of its annual repair and maintenance. Such systems are termed as no-regret options for CO_2 emissions mitigation (Kandpal and Garg, 2003). For a solar dryer to be a no-regret option its net annual cost as expressed by Eq. (10) should be equal to zero (break-even condition) or negative. The following break-even values of different parameters for making the solar drying option a no-regret option (for the purpose of CO_2 emissions mitigation) have been obtained by equating the right hand side of Eq. (10) to zero and solving for the corresponding parameter.

(a) Capacity utilization factor, $BE_{CUF,i}$

$$BE_{CUF,i} = \frac{p_c(CRF_{d>T} + m)}{365I\eta_d p_{f,i}} \quad (12)$$

(b) Cost of solar dryer per unit aperture area, $BE_{pc,i}$

$$BE_{pc,i} = \frac{365I\,CUF\eta_d p_{f,i}}{\eta_i(CRF_{d,T}+m)} \quad (13)$$

(c) Price of ith fuel, $BE_{pf,i}$

$$BE_{pf,i} = \frac{p_c(CRF_{d,T}+m)\eta_i}{365ICUFg_d} \quad (14)$$

3. Assumptions and input parameters

It is assumed that only the farmers having a minimum land holding of two hectares can afford to invest in a solar dryer for farm drying of crops. However, all the commercial users of drying equipment are expected to have sufficient purchasing power to invest in a solar dryer. Since the values of the factors f_p and f_{sol} may be different for different states in India, a weighted average of $f_{pp}f_{sol}$ values for different states has been used in Eq. (1). Table 1 presents the values of f_r and the average value of the product $f_{pp}f_{sol}$ as obtained from a detailed analysis of solar radiation data (Mani and Rangarajan, 1982) and the landholding distribution in India (MOA, 2002; www.tea-india.org; www.indiacoffee.org; www. indianspices.com). Table 1 also presents the values of annual crop production, initial moisture content, final moisture content, drying temperature, fraction of energy supplemented by solar dryer for several crops as reported in the literature. For chilli and turmeric, the respective fractions of total production of these crops dried commercially for powder making are considered for solar drying. Estimates for the capacity utilization factor of solar drying systems for different crops (on the basis of the length of the harvesting season of the crop) are also given in Table 1. Different sources of energy currently being used for crop drying (as a fraction of total dried crop) are also presented in Table 1. An ambient temperature of 25 °C has been used in all calculations.

An average value of 19.8 MJ/m^2 for the daily total solar radiation has been used for sizing the solar dryers. For all crops, thermal efficiency of solar dryer has been assumed to be 0.50 and the dryer is expected to be operational for 10 years (Palaniappan and Subramanian, 1998a). An indirect type solar dryer has been considered for cost estimation. In an indirect type solar dryer the air is first heated in a flat plate collector type solar air heater and it is then passed into a separate drying chamber containing the crop. If the desired drying temperature is not achieved by solar energy then other auxiliary source(s) may be used for further increasing the air temperature. The cost of a typical indirect type solar crop dryer was reported as Rs 3250/- [1] per m^2 of aperture area in the

[1] 1 US$ = Rs 46.29 on 8 July 2003.

Table 1
Some crop specific input parameters used in the calculations

Crop	Q_{tot}[a] (million tonne)	M_i[b] (fraction)	M_f[b] (fraction)	f_{esc} (fraction)	T_d[b] (°C)	CUF[b] (fraction)	f_{pp} f_{sol} (fraction)	f_r (fraction)	Fraction of crop dried with[d]				
									Sun drying	Fuelwood	Coal	L.D.O.	Natural gas
FCV tobacco	0.13	0.090	0.130	0.12	65	0.25	0.900	0.08	0.090	0.16	0.67	0.09	0.08
Coffee (dry process)[e]	0.29	–	–	1.00	40	0.1	0.61	0_0400	0.100	0.15	0.15	0.10	0.00
Coffee (wet process)[e]	0.29	-	-	1.00	40	0.41	0.61	0.00	0.100	0.15	0.15	0.10	0.00
Tea	0.78	0.780	0.03	0.25	100	0.77	0.23	0.00	0.00	0.10	0.100	0.10	0.00
Grapes raisin	1.14	0.80	0.15	0.80	.0	0.25	0.72	0.00	0.80	0.00	0.00	0.00	0.00
Onion flakes	4.90	0.80	0.10	1.00	55	0.33	0.95	0.995	0.00	0.00	0.00	1.00	0.00
Garlic flakes	0.46	0.80	0.04	1.00	55	0.16	0.98	01.000	0.00	0.00	0.00	1.00	0.00
Ginger	0.23	0.80	0.10	1.00	65	0.230	0.34	0_0650	1.00	0.00	0.00	0.00	0.00
Small cardamom	0.008	0.70	0.20	0.50	50	0.41	0.42	0.0080	0.00	0.0	0.00	0.00	0.00
Coriander seeds	0.31	0.18	0.05	0.00	60	0.12	0.82	0.00	0.310	0.100	0.100	0.310	0.00
Black pepper	0.06	0.71	0.13	1.00	40	0.37	0.31	0.00	1.00	0.00	0.00	0.00	0.00
Chilli	0.78	0.780	0.08	1.00	60	0.41	0.97	0.00	0.10	0.100	0.100	0.10	0.00
Turmeric	0.49	0.80	0.10	1.00	60	0.41	0.98	0.80	0.10	0.490	0.490	0.10	0.00

[a] *Sources:* MOA (2002), Singhal (1999), www.indiancoffee.org, and www.teaindia.org.
[b] *Sources:* Alwar and Naidu (1998), Malik et al. (1980), Mande et al. (1999), Singh and Singh (1996), Palaniappan and Subramanian (1998a,b), and Pangavhane and Sawhney (2002).
[0] *Sources:* Bansal (1999), Palaniappan and Subramanian (1998a), and Siddiqui (2001).
[d] *Sources:* ITGA (1997), Mande et al. (2000), Palaniappan and Subramanian (1998a,b), and Singh and Singh (1996).
[6] Total coffee production, the moisture removed per kg of cleaned coffee in dry and wet process are reported 3.10kg and 1.20kg respectively (Alwar and Naidu, 1998).

year 1998 and its annual operation and maintenance cost was around 5% of the capital cost (Palaniappan and Subramanian, 1998b).

Thermal efficiency of a traditional tobacco curing barn (coal and fuelwood based) is reported to be 19% (Bhattacharya et al., 1999). The reported value of the average thermal efficiency of the furnaces used for curing of small cardamom is 6% (Rao et al., 2001). For other crops, thermal efficiencies of conventional drying systems based on fuelwood, coal, light diesel oil (L.D.O.) and natural gas are assumed to be 50%, 60%, 70% and 80% respectively. Carbon emission factors (CEFi) used are 0.0258, 0.0202 and 0.0153 kg/MJ for coal, L.D.O. and natural gas respectively (ADB, 1998) and the values of FCO_i used for coal, L.D.O., natural gas are 0.90, 0.99, 0.99 respectively (ADB, 1998). The market prices for fuelwood, coal, light diesel oil and natural gas have been taken as Rs 0.09/MJ, Rs 0.27/MJ, Rs 0.42/MJ and Rs 0.12/MJ respectively.

4. Results and discussion

The procedure outlined in Section 2 of this paper can, in principle, be used to estimate the potential of using solar dryers for any crop. However, estimation of the three different correction factors requires detailed relevant data on the crops (production levels, drying characteristics etc.), purchasing power of the potential users and solar radiation availability at desegregated levels. Similarly, for estimating the fuel savings and CO2 emissions mitigation potential, the prevailing fuel mix used for drying of the crop(s) should be known. The landholding required to ensure affordability of a solar dryer

Table 2
Potential of solar crop drying in India (aperture area of solar dryers and amount of crop)

Crop	Mass basis used for calculation	Total potential amount (million tonne)	Useful energy requirement for drying (MJ/kg)	Aperture area of solar dryer (m^2)	Unit cost of solar drying (Rs/kg)	Fossil CO_2 emissions from fuel(s) saved (tonne)	Unit cost of CO_2 emissions mitigation (Rs/kg)
FCV tobacco	Dry	0.130	20.35	351355	1.87	100050	-1.23
Coffee (dry process)	Dry	0.106	7.68	550113	3.58	29 .85	29.85
Coffee (wet process)	Dry	0.071	2.98	142283	1.39	6695	29.85
Tea	Dry	0.179	9.65	160632	0.62	36392	-11.51
Grapes raisin	Wet	0.098	1.91	208231	1.46	0	–[a]
Onion flakes	Wet	0.023	1.95	38038	1.13	4751	-0.30
Garlic flakes	Wet	0.023	1.98	77931	2.37	4720	20.33
Ginger	Wet	0.051	1.96	131706	1.79	0	–[a]
Small cardamom	Dry	0.003	4.18	4743	0.98	0	–[a]
Coriander	Dry	0.253	0.43	251774	0.69	7340	–[a]
Black pepper	Dry	0.018	4.96	65515	2.56	0	–[a]
Chilli	Dry	0.454	4.23	2774850	4.23	276406	4.09
Turmeric	Dry	0.286	4.11	1702403	4.11	169 578	4.09

[a] Since net fossil CO_2 emissions mitigation is negative the unit cost of CO_2 emissions mitigation is not worked out.

Table 3
Unit cost of fossil CO_2 emissions mitigation and break-even values of capacity utilization factor, cost of solar dryer and market price of fuel for different crops and fuels replaced by solar dryer

Fuel replaced	Crop(s)	CUF (fraction)	g_i (fraction)	UC_{mit} (Rs/kg)	$BEi_{,CUF}$ (fraction)	$BEi_{,pc}$ (Rs/m^2)	$BEi_{,pf}$ (Rs/MJ)
Coal	FCV tobacco	0.25	0.19	-1.64	0.13	6034	0.15
	Coffee, chilli, turmeric	0.41	0.60	0.15	0.43	3134	0.28
	Tea	0.77	0.60	-1.60	0.43	5885	0.15
Light diesel oil	Garlick flakes	0.16	0.70	20.33	0.32	1631	0.84
	FCV tobacco	0.25	0.70	2.93	0.32	2548	0.54
	Onion flakes	0.33	0.70	-0.30	0.32	3363	0.41
	Coffee, chilli, turmeric	0.41	0.70	-1.77	0.32	4178	0.33
	Tea	0.77	0.70	-3.95	0.32	7847	0.17
Natural gas	FCV tobacco	0.25	0.80	29.11	1.28	637	0.61

Table 4
Future projection of dissemination of solar dryers for cash crops in India and corresponding fuel savings

Crop	Year 2005						Year 2010					
	Qdry (tonnes)	A_a (000 m^2)	Fuel saved				Qdry (tonnes)	A_a (000 m^2)	Fuel saved			
			Fuel wood (tonnes)	Coal (tonnes)	LDO (tonnes)	Natural gas (000 SCM[a])			Fuel wood (tonnes)	Coal (tonnes)	LDO (tonnes)	Natural gas (000 SCM)
FCV tobacco	163	0.44	20.94	68.44	0.793	0.95	293	0.793	37.68	123.16	1.86	1.71
Coffee (dry process)	133	0.69	19.15	12.46	2.95	0.00	239	1.24	34.47	22.42	5.30	0.00
Coffee (wet process)	89	0.18	4.95	3.22	0.76	0.00	760	0.32	8.92	5.80	1.37	0.00
Tea	225	0.20	28.01	22.77	1.62	0.00	405	0.36	50.41	40.98	2.91	0.00
Grapes raisin	123	0.26	0.00	0.00	0.00	0.00	222	0.47	0.00	0.00	0.00	0.00
Onion flakes	29	0.05	0.00	0.00	1.64	0.00	53	0.09	0.00	0.00	2.95	0.00
Garlic flakes	28	0.10	0.00	0.00	1.63	0.00	51	0.18	0.00	0.00	2.93	0.00
Ginger	64	0.17	0.00	0.00	0.00	0.00	115	0.00	0.00	0.00	0.00	0.00
Small cardamom	4	0.01	9.18	0.00	0.00	0.00	8	0.01	16.51	0.00	0.00	0.00
Coriander	317	0.32	6.84	4.45	0.39	0.00	570	0.57	18.01	8.01	0.71	0.00
Black pepper	22	0.08	0.00	0.00	0.00	0.00	40	0.15	0.00	0.00	0.00	0.00
Chilli	569	3.48	257.65	167.58	14.87	0.00	1024	6.26	463.67	301.57	26.75	0.00
Turmeric	359	2.13	158.07	102.81	9.12	0.00	646	4$_2$84	284.47	185.02	16.41	0.00
Total	2125	8.10	504.79	381.72	34.01	0.95	3825	14.57	908.44	686.96	61.20	1.71
Fossil CO_2 emissions mitigation (tonne)				666.25	108.05	2.21				1199.00	194.45	3.98

[a] SCM: standard cubic meters (defined as heating value of one SCM natural gas is 10,000kcal).

may actually vary with the crop and location. It may therefore be necessary to make efforts for obtaining detailed authentic data for such studies. Results of some calculations based on the available estimates of different input parameters are presented in this section.

Table 2 presents the potential amounts of different cash crops that can be dried using solar energy. Useful energy required for drying of unit amount of crop, the aperture area of solar dryers required for drying the estimated potential and the unit cost of solar drying are also given in this table. As expected, the useful energy requirement strongly depends upon the initial and final moisture content of the crop. The useful energy requirement for drying is minimum for coriander (0.43MJ/kg) and it is maximum for flue cured Virginia (FCV) tobacco (20.35 MJ/kg). The estimates for unit cost of solar drying are found to vary from Rs 0.62/kg for tea to Rs 4.23/kg for chilli.

Copper, aluminum, toughened glass, glass wool, absorber paint are commonly used materials for making an indirect type solar dryer. On the basis of the inventory of the amounts of different materials used and their respective energy intensities the embodied energy in a solar dryer has been estimated at 2968.7MJ per m^2 of aperture area. Using the values for CO2 emission factors for different materials as available in the literature the total embodied CO_2 emissions for solar dryer has been estimated at 436.2kg/m^2 of aperture area. Estimates of the likely savings in fossil CO_2 emissions due to substitution of fossil fuels by the use of solar dryers and the corresponding unit cost of CO2 emissions mitigation are also presented in Table 2. Since biofuels (such as fuelwood, biomass briquettes etc.) are net zero carbon emitters the CO_2 emissions due to the use of fuelwood for crop drying have not been considered in this analysis. The unit cost of fossil CO_2 emissions mitigation by the use of solar dryer is found to be minimum (Rs — 11.51/kg) for tea drying. A negative value of unit cost of net fossil CO2 emissions mitigation indicates that the annualized cost for solar dryer (including repair and maintenance cost) is less than the costs of annual amount of different fuels saved by the solar dryer. Due to predominant sun and fuelwood based coffee drying in India the unit cost of net fossil CO2 emissions mitigation by solar dryer is highest (Rs 29.85/kg) for coffee drying.

Separate estimates of the unit cost of fossil CO_2 emissions mitigation for different fuels are presented in Table 3. It may be noted that the unit cost of CO2 emissions mitigation is lowest (Rs —3.95/kg) for the case of light diesel oil replacement for drying tea. The unit cost of fossil CO_2 emissions mitigation is highest (Rs 29.1 1/kg) for the replacement of natural gas in FCV Tobacco drying due to low carbon emission factor, low market price and high thermal efficiency of utilization of natural gas. The amount of fuel replaced by solar dryer increases with an increase in its capacity utilization factor leading to a reduction in the net annual cost of dryer and an increased fossil CO2 emissions mitigation. Therefore, the unit cost of fossil CO_2 emissions mitigation decreases with an increase in capacity utilization factor of a solar dryer. Break-even values of capacity utilization factor, cost of solar dryer (Rs/m^2 aperture area) and prices of different fuels (Rs/MJ) for making the solar dryer a no-regret option are also presented in Table 3. The minimum break-even value of capacity utilization factor is 0.13 for the case of coal being replaced by a solar dryer for drying FCV Tobacco. This essentially means that for FCV tobacco, the replacement of coal by a solar dryer would be a no-regret option so long as capacity utilization factor is higher than 0.13 (provided other parameters remain the same).

From the available indicative past data (MNES, 2001) on the dissemination of solar dryers in the country it is noted that the dissemination of solar crop dryers is increasing at a compounded growth rate of 12.47%. The same value is used for future dissemination of solar crop dryers in India for next ten years. Table 4 presents the projected levels of solar dryer dissemination in India for the years 2005 and 2010 with corresponding amounts of fuels that would be saved. The likely mitigation in gross CO2 emissions for the respective years is also presented in this table. The estimation of maximum potential of solar drying of the selected cash crops is based on the existing data for crop production. While considering the time variation of cumulative installation of solar dryers any possible change in the crop production and its end usage(s) with time have not been considered in the study.

5. Concluding remarks

There is a large potential of using solar energy for drying of cash crops in India. Due to unavailability of reliable detailed data only a limited number of cash crops have been considered in this study. The total solar drying potential is expected to be much higher. Solar drying can play an important role in saving biofuels and fossil fuels presently used in the drying of FCV tobacco, coffee and tea. It may also be noted that though some of these crops are presently being sun dried, there is a very large potential of solar drying of these crops for avoiding losses during sun drying. There is also a possibility of using solar dryers at community level to offset the problem of poor capacity utilization of dryers and low individual purchasing power of the majority of the potential users. However, the same has not been included in this study. Actual identification of niche areas and sites for intervention in the initial phase would also require consideration of a variety of other site-specific features.

Appendix A. Expression for unit cost of solar drying on wet mass basis of a crop

The useful energy required for drying unit amount of wet crop (UE_{dry}) can be estimated by the following expression

$$UE_{dry} = \left(\frac{M_i - M_f}{1 - M_f}\right) h_{fg} + s(T_d - T_a) \quad \text{(A.I)}$$

The aperture area of solar dryer (A_c) for drying Q_{dry} amount of wet crop can be estimated as

$$A_a = \left(\frac{f_{es} Q_{dry} UE'_{dry}}{365 I CUF \eta_d}\right) \quad \text{(A.2)}$$

The unit cost solar crop drying (UC_{dry}) for wet mass basis of a crop is

$$UC_{dry} = \frac{f_{es} UE_{dry} p_c (CRF_{d,T} + m)}{365 CUF I \eta_d} \quad \text{(A.3)}$$

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