ARTICLE IN PRESS

Energy Policy ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Solar lanterns for domestic lighting in India: Viability of central charging station model

A. Chaurey [a,1], T.C. Kandpal [b,*]

[a] TERI, Darbari Seth Block, Habitat Place, Lodhi Road, New Delhi 110003, India
[b] Centre for Energy Studies, Indian Institute of Technology, Hauz Khas, New Delhi 110016, India

ARTICLE INFO

Article history:
Received 26 March 2009
Accepted 16 June 2009

Keywords:
Solar lanterns
Fee-for-service
Central charging station

ABSTRACT

About 68 million households in India rely on kerosene as a fuel for domestic lighting. Kerosene-based lighting devices, not only for poor quality of light, but also for the risks of indoor air pollution and fire hazards, etc. are not a desired option for domestic lighting purposes. Solar lantern is a better alternative in terms of its quality of illumination, durability and versatility of use. The dissemination model for solar lantern in India has so far been based on cash sales with or without the incentive of capital subsidy. This paper analyses several dissemination models including rental and fee-for-service based on centralized solar charging station concept for CFL- and LED-based designs of solar lanterns available in India. The basis of comparison is the acceptable daily costs or rental to the user as well as to the owner of the charging station. Further, the paper studies the impact of likely escalation in kerosene price on the acceptable daily rental and estimates the amount of subsidy required to make the charging station model viable for disseminating solar lanterns among rural households.

1. Introduction

About 67.6 million rural households in India rely on kerosene as fuel for lighting (NSSO, 2008). Till such times as access to electricity or other forms of lighting is provided, kerosene continues to provide social and economic benefits to these households associated with lighting. However, kerosene, as a lighting fuel is not only inefficient in terms of cost per useful energy (Dutt, 1994), but also has adverse implications on the national economy due to associated subsidy burden. Besides, there are hazardous incidents of fire due to spillage of kerosene from wick lamps, accidental drinking of kerosene by children, indoor smoke related problems, etc. reported not only in India, but also from other developing countries such as South Africa, Argentina, Senegal, and Kenya where a large population uses kerosene for domestic lighting (GNESD, 2009).

Solar lantern, due to its portability and versatility of use, is a potential option for replacing kerosene-based devices for domestic lighting applications. A solar lantern is a portable lighting device using either CFL- or LED-based luminaire, housed in an enclosure made of plastic or metal that contains a rechargeable battery and necessary electronics. The rechargeable battery is charged using a separate PV module by connecting it through an electric plug-and-socket arrangement. In some of the designs, the PV module is integrated into the top-cover of the lantern itself making it a self contained integrated unit. Table 1 presents a comparison of kerosene-based and solar lanterns on the basis of several characteristics desired by the potential users of domestic lighting devices.

Design and development of solar lanterns in India was initiated in 1991 under the national programme on SPV demonstration (DNES, 1992). A total of about 0.697 million solar lanterns were disseminated in the country as on January 2009 (MNRE, 2009). Considering the total number of rural households that use kerosene for lighting in India (67.6 million), the number of solar lanterns reportedly disseminated so far is miniscule. The dissemination of solar lanterns has faced challenges related to operational, financial and marketing aspects. Lack of awareness among prospective users, limited outlets for procurement, unavailability of different models catering to varying needs among various user segments, high price and limited hours of usage were some of the reasons cited for poor dissemination of solar lanterns in the country (Rubab and Kandpal, 1996; Velayudhan, 2003).

2. Dissemination models for solar lanterns

Solar lanterns are mostly disseminated through the ownership model where the lanterns along with PV module are sold directly to the user either at full cost or at a subsidized cost. The fee-for-service/rental model where solar lanterns are recharged or rented to the user for a fee is relatively uncommon. The fee-for-service/

---

* Corresponding author. Tel.: 91 11 26591262; fax: 91 11 26582037.
E-mail addresses: akanksha@teri.res.in (A. Chaurey), tarak@ces.iitd.ernet.in (T.C. Kandpal).

[1] Tel.: 91 11 24682100; fax: 91 11 24682144.

0301-4215/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2009.06.047

Please cite this article as: Chaurey, A., Kandpal, T.C., Solar lanterns for domestic lighting in India: Viability of central charging station model. Energy Policy (2009), doi:10.1016/j.enpol.2009.06.047

Table 1
Comparison of kerosene and solar lanterns.

Characteristic	Kerosene lantern	Solar lantern
Capital cost	Low	High
Cost of fuel	Depends on usage	Nil
Replacement cost	Low (replaceable items being glass chimney, cotton wick)	High (replaceable items being battery, CFL)
Availability and reparability	Very good, even in remote locations	Poor, due to limited sale and servicing outlets
Flexibility to reduce illumination	Possible, by lowering the wick	No option for dimming the illumination in CFL-based lanterns, possible in LED-based lanterns
Lumen output	Low	4–5 times higher
Safety aspects	Fire and health hazards due to smoke	Safe to use
Subsidy burden	Recurring burden of fuel subsidy	One time burden of capital subsidy (if provided)

Table 2
Comparison of ownership and fee-for-service models for dissemination of solar lanterns.

Characteristic	Model	
	Ownership	Fee-for-service/ rental
Initial cost burden	User owns the lantern by paying full cost of it	User does not own the lantern, but rents it by paying a fee as and when required
O&M cost	User has to pay for O&M of the lantern throughout its useful life, and hence is careful while using it thereby ensuring the longevity of lantern and its components	User usually does not bear any cost towards O&M and tends to misuse or mishandle it while using, often resulting into reduced life of its components
Spatial and temporal flexibility to use	User can use the lantern anywhere and at any time	User can use the lantern only after procuring it from the charging station
Recharging of battery	User has to recharge the lantern by keeping the PV module outside in the sun daily, by ensuring proper orientation	User does not have to worry about recharging the lantern, except for delivering the lantern to the charging station
Safety	User is responsible for the safety of PV module	User is not responsible for the safety of the module

rental model for dissemination of solar lanterns in India was piloted in early 1990s in a remote village in the Sunderbans region of West Bengal where a centralized charging station for 40 solar lanterns was set up by an NGO (Mukhopadhyay et al., 1993). It was further demonstrated by the same NGO in two more villages in the same region (TERI, 2004). Recently, this model for dissemination of solar lanterns has been adopted for a global programme called "Lighting a Billion Lives (LaBL)" in which such stations have already been set up in 100 villages across various states in India (LaBL, 2009).

Even though the ownership model has so far prevailed for dissemination of lanterns, there are both advantages and disadvantages of this model as compared to fee-for-service or rental model. While the owner of the lantern has the freedom to use solar lantern as and when and wherever desired, the user of the charging service has to confine the lantern usage within the rented duration and location. A user may also run the risk of not getting the lantern on rent when required due to unavailability of lanterns for rental. Walking up to and from the charging station with the lantern could also be inconvenient. However, one of the most significant points in favor of fee-of-service is the third party maintenance (Roy and Jana, 1998). Another advantage of fee-for-service model is the flexibility to rent or recharge the lantern (and, therefore, pay for the services) only when required. In Senegal, a facility was set up under the French foreign assistance programme wherein users could either bring their own lanterns for recharging or could hire out recharged lanterns if they were either unwilling or unable to own them (Dutt and Mills, 1994). This might be more acceptable to a large population of rural households across many developing countries that purchase kerosene in small quantities as and when required, depending on their affordability. The fee-for-service or rental model necessarily requires an institutional set up and an infrastructural facility in the form of a Centralized Charging Station (CCS) to recharge solar lanterns and rent out. Table 2 presents a comparison of ownership vs. fee-for-service models.

3. Viability of centralized charging station (CCS) model for solar lanterns

3.1. Basic concept

The concept of CCS works on the model of fee-for-service or renting where the user either owns the solar lantern and recharges its battery by paying a fee or does not even own the lantern and rents a charged lantern, as and when required, from the charging station. In both the cases, the user does not own the PV module as in the case of ownership model. PV modules adequately sized for the number and configuration of lanterns to be charged are installed preferably at a central location in the village to make it convenient for the users to come on a daily basis. The CCS is operated and managed by an individual or a group of individuals who would either recharge the lantern for a fee or rent the charged lantern for a daily rental amount to the households.

3.2. Design features

The design of CCS would incorporate installation of PV modules in a specific voltage and current configuration to charge a number of lanterns either in series or in parallel. Charge controllers for all the lanterns would ensure that each lantern is adequately and properly charged. The charge controllers would be housed inside a junction box that will also have sockets to plug-in the leads for individual solar lanterns. This integrated charge controller-cum-junction box (ICCJB) is hence the heart of the CCS that controls and coordinates all inflow and outflow of energy and ensures its proper function. The design of CCS should be able to

(a) accept and charge any number of lanterns (up to the maximum number it is designed for) at any time without damaging the lanterns already connected to the junction box,
(b) protect battery of each individual lantern from overcharge irrespective of the number of lanterns already connected,
(c) charge all connected lanterns irrespective of the state of charge of their respective batteries, and
(d) indicate clearly and individually the charging status of each connected lantern.

The design philosophy as well as the architecture of CCS has undergone changes from its earlier pilots to the current initiatives. For instance, the first pilot at Sunderbans was designed to connect all lanterns in series and provision was made to bypass charging current from sockets without any lantern or with fully charged lanterns. The current designs use micro-controller circuits to

Please cite this article as: Chaurey, A., Kandpal, T.C., Solar lanterns for domestic lighting in India: Viability of central charging station model. Energy Policy (2009), doi:10.1016/j.enpol.2009.06.047

Box 1–Cost-factors for owning vs. renting a solar lantern

In a recent World Bank Group initiative called Lighting Africa, it is reported that prospective consumers found solar lanterns to be their preferred lighting option, but the maximum amount which they are willing to spend on any type of modern lighting device is around US$ 7.50 (Lighting Africa, 2008). Twelve of the 16 projects that were awarded the Development Marketplace (DM) grant in May 2008 under this initiative, use LED-based lighting products powered by solar PV. Further, it is proposed to make these products and services accessible to the poor communities through renting/fee-for-service model or micro-finance aided purchase model (Development Marketplace, 2008). Experiences compiled from five different villages spread in different states in India where Lighting a Billion Lives (LaBL) initiative has been implemented, suggest that solar lanterns are popular among users if these are made available on a daily basis at small amounts of money equivalent to the household's expenditure on kerosene and candles (Lucas, 2008). Households that were using, on an average daily basis, 2 wax candles at a cost of Rs. 2.50 each, found the daily rental charge of Rs. 3 cheaper. This rent was also found affordable by households using about 4 l of kerosene per month bought at a market price of Rs. 28 per litre. However, for below poverty line households that are eligible to procure subsidized kerosene of upto 3 l per month at a unit price of Rs. 11 per litre, the rental of solar lantern was found to be unaffordable.

ensure adequate flow of current in each connected lantern without damaging any battery. A few other advantages of CCS design over individually owned solar lanterns with PV modules are:

- The fixed installation of PV modules in a CCS ensures their proper orientation and tilt to maximize the solar gain at a location. However, it may not be ensured in individually owned and used small capacity PV modules of solar lanterns which are required to be kept out in the sun everyday by the user and taken indoors after the sunset.
- Large capacity PV modules (37–100 Wp) typically used in total PV array required for CCS offer better unit costs in terms of Rs./Wp and usually better efficiencies as compared to small capacity modules (3–10 Wp) that are used with individual lanterns.
- In case of a CCS, excess energy from PV modules, when the lanterns are not available for charging, can be utilized for some other purpose such as charging of batteries. This flexibility is not available with individually owned solar lanterns.
- Monitoring of performance and usage of solar lanterns, in case required for techno-economic evaluation, carbon financing, etc. would be easier in CCS dissemination model as compared to individually owned and used solar lanterns.
- The risk of theft of PV modules is relatively much less in CCS model.

3.3. *Financial viability of CCS*

The financial viability of CCS for disseminating solar lanterns needs to be analyzed from the perspective of the user as well as from that of the owner (or entrepreneur) of the charging station. A comparison of annual costs of owning vs. renting and/or charging the lanterns is likely to be made by the user, while the entrepreneur will evaluate the viability on the basis of net revenue from selling the services. Experiences from two recent initiatives provide an idea of the cost factors for owning vs. renting/charging (Box 1).

3.3.1. *Viability from the user's perspective*

As mentioned earlier, a potential user of the solar lantern has two options:

- Ownership—He/she owns the lantern along with the PV module by paying full cost of it and maintains it throughout its useful life, and
- Renting (Case I) or fee-for-service (Case II)—He/she uses the charged solar lantern by paying a daily rental or charging fee to the CCS entrepreneur. Characteristics of rental and fee-for-service models are presented in Table 3.

Table 3
Models of central charging station.

	Rental (Case I)	Fee-for-service (Case II)
CCS owner/ entrepreneur	• Owns the CCS by paying full costs of PV modules, ICCJB and lanterns • Performs the O&M of the PV modules, ICCJB and lanterns • Keeps all revenues collected from renting the lanterns	• Owns the CCS by paying full costs of PV modules, and ICCJB only • Performs the O&M of PV modules and ICCJB • Keeps all revenues collected from recharging the lanterns brought to the CCS by the user
Lantern user	• Does not own the lantern, but rents the charged lantern from the CCS as and when required • Does not bear any costs towards maintenance of the lantern, PV modules and ICCJB	• Owns the lantern, gets it recharged from the CCS as and when required • Bears all costs towards maintenance of the lantern

To evaluate the viability from the user's perspective, the effective daily costs of using the lantern in all the above cases are compared using the Annualized Life Cycle Cost (ALCC) as the index for comparison. The ALCC is estimated by summing up costs of all components in a lantern (i.e., PV module, battery, CFL and PCB) multiplied by their respective Capital Recovery Factors[2] using the following expression:

$$\mathrm{ALCC} = C_{0\mathrm{pv}} \times \mathrm{CRF}_{\mathrm{pv}} + C_{0\mathrm{batt}} \times \mathrm{CRF}_{\mathrm{batt}} + C_{0\mathrm{cfl}} \times \mathrm{CRF}_{\mathrm{cfl}} + C_{0\mathrm{pcb}} \times \mathrm{CRF}_{\mathrm{pcb}} \quad (1)$$

where C_0 and CRF with their respective subscripts, represent capital costs and capital recovery factors for PV, battery, CFL and PCB. CRF for each component is calculated at chosen discount rate and the useful life of that particular component. Two popular solar lanterns, one with 7 W CFL and the other with 2.5 W LED are considered for the analysis. The capital costs of these two models estimated on the basis of information collected from manufacturers and suppliers of lanterns and from the results of a recently published survey (Gaur and Marcus, 2008) are presented in Table 4. Accordingly, costs of 7 W CFL and 2.5 W LED lanterns along with their respective PV modules are estimated to be Rs. 3300 and Rs.1600, respectively.

---

[2] CRF is calculated using the expression $\{i(1+i)^n/[(1+i)^{n-1}]\}$, where i represents the chosen discount rate and n is the life of the particular component being considered.

Please cite this article as: Chaurey, A., Kandpal, T.C., Solar lanterns for domestic lighting in India: Viability of central charging station model. Energy Policy (2009), doi:10.1016/j.enpol.2009.06.047

Table 4
Annualized life cycle costs of lanterns.

	Cost (Rs.) C_0	Life (yr) N	CRF (fraction)	Annual cost (Rs.)
Model—7 W CFL lantern				
Module—10 Wp	2200	20	0.1339	294.53
Battery—12 V, 7Ah	640	5.1	0.2719	174.03
CFL—7 W	70	5.1	0.2719	19.03
PCB	200	10	0.1770	35.40
Housing, cable, etc.	190	20	0.1339	25.44
ALCC (total)	3300			548.43
ALCC (lantern)				253.89
Model—2.5 W LED lantern				
Module—3 Wp	750	20	0.1339	100.41
Battery—6 V, 4.5 Ah	170	2.6	0.4752	80.78
LED—2.5 W	350	25.7	0.1269	44.43
PCB	180	10	0.1770	31.86
Housing, cable, etc.	150	20	0.1339	20.08
ALCC (total)	1600			277.54
ALCC (lantern)				177.13
Assumptions				
Life of 7 W CFL	5.1 yr @ 6000 burning hours for 4 h/day, 292 days/yr			
Life of 2.5 W LED	25.7 yr @ 30,000 burning hours for 4 h/day, 292 days/yr			
Life of 12 V, 7 Ah battery	5.1 yr @ 1500 cycles @ 50% DoD, 292 days/yr			
Life of 6 V, 4.5 Ah battery	2.6 yr @ 800 cycles @ 50% DoD, 292 days/yr			
Discount rate	12%			

The ALCC of owning the lantern is estimated to be Rs. 548.43 and 277.54, respectively, for the 7 W CFL and 2.5 W LED lanterns (Table 4). Their effective daily cost ($E_{ff}DC$) to the user is estimated to be Rs. 1.88 and 0.95, respectively, for 7 W CFL and 2.5 W LED lanterns using the following expression:

$$E_{ff}DC = \left(\frac{ALCC}{365 \times CUF}\right) \tag{2}$$

The Capacity Utilization Factor (CUF) in CCS model of dissemination would depend on the availability of lanterns for renting, and the variability of the need of the users. Factors such as inadequate solar radiation leading to partially charged or uncharged lanterns; faults in the lanterns and/or CCS would lead to lanterns not being available for renting. Users, on the other hand, may not always rent the lanterns. They may not have enough money, they may be out of station, or they may simply not need a lantern on a particular day. The CUF of CCS in this analysis is assumed to be 0.8.

In order to compare the viability of ownership model with the rental (Case I) and fee-for-service (Case II) from the user's perspective, it is assumed that the maximum acceptable daily rental that the user would be willing to pay, should be equal to the effective daily cost of owning the lantern for the same quality and quantity of service. Hence, for Case I, the upper limit of acceptable daily rental ($UADR_I$) to the user would be

$$UADR_I = E_{ff}DC \tag{3}$$

For Case II, the upper limit of acceptable daily rental ($UADR_{II}$) to the user can be estimated as

$$UADR_{II} = E_{ff}DC - \left(\frac{ALCC_{lantern}}{365 \times CUF}\right). \tag{4}$$

$ALCC_{lantern}$ represents the annualized life cycle cost of the lantern alone. Accordingly, it is estimated that in Case I, the user would be willing to pay a maximum of Rs. 1.88 daily for renting the 7 W CFL lantern, while the corresponding amount would be Rs. 0.95 for 2.5 W LED lantern. For Case II, these amounts would be Rs. 1.32 and 0.56, respectively, which are 70% and 59% lower than the corresponding values for Case I. The above set of numbers is arrived at by assuming specific values of input parameters, i.e. cost and useful lives of individual components, and discount rate (Table 4). Considerable variation in the values of these parameters is expected. For instance, the cost of PV module shows a large variation in small capacity range as reported in a recent survey (Gaur and Marcus, 2008). Further, there are reports of premature degradation in PV modules, thereby reducing their effective life (Rentzing, 2008). The life of battery (specified in number of cycles) depends on, among other factors, the depth of discharge it is being subjected to. Similarly, any variation in the discount rate would also affect the viability of using solar lanterns from the user's perspective as well as from the CCS entrepreneur's perspective.

3.3.2. *Viability from the entrepreneur's perspective*

The analysis from the entrepreneur's perspective is also performed in terms of estimating the total annual costs involved in operating and maintaining a CCS with a specified number and type of lanterns. This analysis is performed for Case I—where CCS includes lanterns; as well as for Case II—where CCS does not include lanterns. The viability of CCS is seen at the lower limit of acceptable daily rental (LADR) or the minimum value of daily rental that the entrepreneur would require to cover his/her costs and makes an acceptable profit. Further, the LADR is compared with different values of rentals and fee that might be acceptable to the user. Practically, the acceptable daily rental (ADR) to the user may be more or even less than LADR. For instance, the households falling under below poverty line category are reported to consume about 3 l of kerosene per month for lighting, purchased at a subsidized price of Rs.11 per litre (Lucas, 2008). Such, households would require a daily rental below LADR for using solar lanterns. On the other hand, some users might be willing to pay more than the LADR in consideration of the convenience of not having to maintain the lanterns.

The above set of analyses are performed and discussed separately for two designs of CCS, one with 50 numbers of 7 W CFL lanterns and the other with 50 numbers of 2.5 W LED lanterns. The design features and costs associated with these charging stations are based on LaBL initiative and discussions with various

PV manufacturers (TERI, 2008). Accordingly, the upfront costs involved in setting up a CCS include equipment and their installation consisting of (i) PV modules along with their mounting structures, (ii) ICCJB having charging circuits and charging chords for connecting lanterns, and (iii) 50 numbers of lanterns. The operation and maintenance costs include salary of an operator, replacement costs of battery and CFL/LED in lanterns, and some minor O&M costs for ICCJB. In addition, a certain margin is to be kept for the CCS entrepreneur to make it an attractive livelihood option.

The above-mentioned costs are valid for rental model (Case I) in which the entrepreneur owns lanterns. The fee-for-service model (Case II) on the other hand, excludes upfront costs of lanterns as well as the replacement costs of their batteries and CFLs/LEDs as these are the responsibility of the owner of lanterns.

The LADR_I is estimated using the following expression:

$$\text{LADR}_\text{I} = \frac{(1+f_\text{m}) \times (\text{ALCC}_\text{ccs} + \text{ASO})}{N_\text{l} \times 365 \times \text{CUF}}, \tag{5}$$

where ALCC_ccs refers to annualized life cycle costs of the complete CCS with PV module, ICCJB and lanterns; ASO, the annual salary of operator; f_m, the fraction of total annual costs of owing and operating the CCS that the entrepreneur would like to keep as livelihood margin; N_l is the number of lanterns in a CCS; and CUF, the annual average capacity utilization factor of the CCS.

Similarly, LADR_II is estimated as

$$\text{LADR}_\text{II} = \frac{(1+f_\text{m}) \times (\text{ALCC}_\text{ccs} - \text{ALCC}_\text{lantern} + \text{ASO})}{N_\text{l} \times 365 \times \text{CUF}}. \tag{6}$$

Accordingly, the LADR_I in Case I for CCS having 7 W CFL lanterns is estimated to be Rs. 4.06, while it is Rs. 3.02 for case II where CCS entrepreneur does not own the lanterns. These values are Rs. 3.33 and 2.60 for CCS with 2.5 W LED lanterns (Table 5). The values are estimated at 20% livelihood margin ($f_\text{m} = 0.20$) and an amount of Rs. 2000 per month paid to a part-time operator (i.e., ASO = Rs. 24,000), engaged for a few hours daily for routine operations at CCS. These values of LADR understandably are sensitive to the livelihood margin as well as the salary given to the CCS operator. A summary of results is presented in Table 6.

It may be noted that there is a significant gap between the maximum amount that a user would want to pay for a specific service (UADR) and the minimum amount that the entrepreneur would require for providing the same service (LADR). One of the potential strategies to bridge this gap would be to provide upfront subsidy to the entrepreneur for setting up the CCS. Other possibilities include overall cost reductions in CCS equipment due to technological advancements or volume effects. An attempt to estimate the potential for diffusion of solar lanterns in the country has been presented in Appendix 1 and in Section 4. The requirement of upfront subsidy to effectively reduce the gap between the minimum daily rental necessary for the sustainability of CCS and the rental acceptable to the user is made in the next section. A CCS with 7 W CFL lanterns is considered for this purpose.

Table 5
Annualized life cycle costs of central charging station (CCS).

	No.	Unit cost (Rs.)	Total cost (Rs.)	
			Case I (rental)	Case II (fee-for-service)
Model—7 W CFL lanterns				
7 W CFL lantern	50	1100	55,000	0
PV modules—80 Wp	5	14,600	73,000	73,000
ICCJB	5	3300	16,500	16,500
Total costs of a charging station			144,500	89,500
ALCC (CCS)			25,388	12,693
ALCC (lanterns)	50	253.89	12,695	
LADR (Rs.)			4.06	3.02
Model—2.5 W LED lanterns				
2.5 W LED lantern	50	850	42,500	0
PV modules—30 Wp	5	7000	35,000	35,000
ICCJB	5	3300	16,500	16,500
Total costs of a charging station			94,000	51,500
ALCC (CCS)			16,463	7606
ALCC (lanterns)	50	177.13	8857	
LADR (Rs.)			3.33	2.60
Assumptions				
Life of CCS	20 yr			
Life of ICCJB	10 yr			
Discount rate	12%			
f_m (livelihood margin)	20%			
Annual salary of operator (ASO)	24,000			
Number of lanterns (N_l)	50			
CUF	0.8			
Effective days of operation of CCS/yr (days in a year *X* CUF)	292			

Table 6
Comparison of maximum and minimum acceptable rental value to the user and CCS entrepreneur.

	CCS with 7 W CFL		CCS with 2.5 W LED	
	Case I	Case II	Case I	Case II
UADR (Rs.)	1.88	1.32	0.95	0.56
LADR (Rs.)	4.06	3.02	3.33	2.60

3.4. *Estimation of capital subsidy for viability of CCS*

It is assumed that the fraction of capital subsidy (f_cs) given for setting up a CCS is equally distributed among all its components (i.e., PV modules, lanterns, and ICCJB). The value of f_cs is estimated using following expressions:

(a) Case I

$$\text{ADR}_\text{I} = \frac{(1+f_\text{m}) \times [(1-f_\text{cs}) \times \text{ALCC}_\text{ccs} + \text{ASO}]}{N_\text{l} \times 365 \times \text{CUF}},$$

or

$$\text{ADR}_\text{I} = \text{LADR}_\text{I} - \left(\frac{(1+f_\text{m}) \times f_\text{cs} \times \text{ALCC}_\text{ccs}}{N_\text{l} \times 365 \times \text{CUF}}\right) \tag{7}$$

(b) Case II

$$\text{ADR}_\text{II} = \frac{(1+f_\text{m}) \times [(1-f_\text{cs}) \times (\text{ALCC}_\text{ccs} - \text{ALCC}_\text{lantern}) + \text{ASO}]}{N_\text{l} \times 365 \times \text{CUF}}$$

or

$$\text{ADR}_\text{II} = \text{LADR}_\text{II} - \left(\frac{(1+f_\text{m}) \times f_\text{cs} \times (\text{ALCC}_\text{ccs} - \text{ALCC}_\text{lantern})}{N_\text{l} \times 365 \times \text{CUF}}\right) \tag{8}$$

The results of this analysis for a CCS with 7 W CFL lanterns are presented in Table 7 based on values for input parameters presented in Tables 4–6. As seen, the CCS model does not seem to be viable for catering to households not able to or not willing to pay a rental of more than Rs. 1.88 per day (i.e., the upper limit of

Please cite this article as: Chaurey, A., Kandpal, T.C., Solar lanterns for domestic lighting in India: Viability of central charging station model. Energy Policy (2009), doi:10.1016/j.enpol.2009.06.047

Table 7
Impact of annual escalation in fuel prices on daily rentals and a comparison of requirement of capital subsidy to the owner of CCS using 7 W CFL lanterns, with and without annual escalation in kerosene price.

	Case I: CCS includes lanterns (lower limit of acceptable daily rental to the CCS owner ($LADR_I$) = Rs. 4.06)				Case II: CCS does not include lanterns (lower limit of acceptable daily rental to the CCS owner ($LADR_{II}$) = Rs. 3.02)			
Sl. no.	Acceptable daily rental to CCS owner without escalation (ADR_I)	Fraction of capital cost required as subsidy (f_{cs})	Acceptable daily rental to CCS owner with escalation (ADR_{baseI})	Fraction of capital cost required as subsidy (f_{cs})	Acceptable daily rental to CCS owner without escalation (ADR_{II}) (0.7*ADR_I)	Fraction of capital cost required as subsidy (f_{cs})	Acceptable daily rental to CCS owner with escalation (ADR_{baseII})	Fraction of capital cost required as subsidy (f_{cs})
1	4.25	-0.09	3.07	0.48	2.98	0.04	2.15	0.92
2	4.00	0.03	2.88	0.56	2.80	0.21	2.02	0.98
3	3.75	0.15	2.70	0.65	2.63	0.37		
4	3.50	0.27	2.52	0.74	2.45	0.54		
5	3.25	0.39	2.34	0.82	2.28	0.71		
6	3.00	0.51	2.16	0.91	2.10	0.88		
7	2.75	0.63	1.98	0.99	1.88			
8	2.50	0.75						
9	2.25	0.87						
10	2.00	0.99						

acceptable daily rental (UADR) if they were to compare the effective daily cost of renting a solar lantern with ownership even if the entire capital cost of setting up the CCS is subsidized. However, if the households value the benefits of renting the lanterns every day and are willing to pay Rs. 4.00 as daily rental, the entrepreneur would be able to run the CCS profitably with negligible (merely 3%) subsidy. For a threshold daily rental of Rs. 2, a CCS set up with 99% capital subsidy breaks even.

In case of fee-for-service (Case II) model, the user would be willing to pay less amount of money for recharging its own lantern as compared to Case I (as expenditure is incurred by the user in purchasing and maintaining the lanterns ($UADR_{II}$ being 70% of $UADR_I$, as discussed in Section 3.3.1). In this case the extent of capital required subsidy is higher as compared to the rental case. Thus the rental model would perhaps be more viable than fee-for-service model from the perspective of overall subsidy burden.

3.5. *Impact of escalation in daily rental on viability of CCS*

In actual practice, due to likely escalation in the price of the fuel (kerosene, in this case) substituted by the solar lantern, it may be possible to upwardly revise the daily rentals of the solar lanterns within the acceptable range of the user. In such a case, an estimation of the extent of capital subsidy required should be made with an internalization of the effect of acceptable increase in daily rental due to escalation in the price of kerosene. This analysis is performed in twp steps for Case I only. First it is assumed that the acceptable daily rental is increased annually by a fraction ζ of its previous value and the impact of this escalation has been estimated using the expression[3]

$$ADR_I = \frac{ADR_{initial}}{(d-\zeta)} \times \left[1 - \left(\frac{1+d}{1+\zeta}\right)^n\right] \times CRF_{d,n}, \qquad (9)$$

where $ADR_{initial}$ is the initial value of daily rental to be charged by the entrepreneur and is subject to escalation and n is the useful life of the lantern. The above expression can be used to work out various combinations of ζ and $ADR_{initial}$ for different values of acceptable daily rentals ADR_I.

Subsequently, in the second step, requirement of subsidy to fill the gap between $ADR_{initial}$ and ADR_I has been worked out. The results are presented in Tables 7 and 8. As seen, the initial rental can be kept about 72% lower if it can be subjected to 5% annual escalation as compared to the case of rental being constant throughout the life of the CCS. In actual practice, due to the volatile crude oil prices, the kerosene price has varied from Rs. 34.15 per litre in October 2008 to Rs. 22 in January 2009 and again to Rs. 29.48 in May 2009 making the solar lantern rental model much more attractive to users purchasing kerosene at the market price. The requirement of upfront subsidy to be given to the CCS entrepreneur is however higher in the former case as compared to the latter, as long as the benefits of annual escalation in the rentals are kept by the entrepreneur.

4. Emerging technological and institutional trends and their impact on the viability of CCS

The study has so far dealt with the viability of disseminating solar lanterns through centralized charging station model in India. It would be worthwhile studying the international developments in similar and related fields that will affect the dissemination of solar lanterns, specifically, the current R&D in PV, lighting and storage devices; innovative approaches in system design; and opportunities for NGOs and corporate houses to participate in a mutually beneficial mode.

4.1. *Global PV market, learning effect and economies of scale*

Solar PV is projected to be among the fastest growing energy technologies in the world. In the year 2008, Global solar PV production increased by 90% to 6.9 GWp (REN21, 2009). Emerging technologies such as thin-films and nano-solar cells are promising to bring down the cost substantially. According to industry analysis, it is possible for an Indian manufacturer to sell PV module profitably at Rs. 145/Wp based on cost structure of crystalline silicon value chain (PowerLine, 2009). Any reduction in PV module prices would positively affect the viability of CCS using large capacity PV modules if not to that of small size PV modules of individually owned solar lanterns. For instance, the total cost of a CCS with reduced PV module price could be 9–10% lower thus lowering the value of LADR for the entrepreneur and consequently reducing the subsidy burden. Similarly, the overall cost reductions

---

[3] If the $ADR_{initial}$ is assumed to be upwardly revised each year by a fraction ζ of its previous year, then the cumulative present worth of cash flows for each lantern considered for a useful life of n years would be represented by $ADR_I = \{[(ADR_{initial}/(1+d)]+[ADR_{initial}(1+\zeta)/(1+d)^2]\ldots[ADR_{initial}(1+\zeta)^{n-1}/(1+d)^n]\}$ or, $ADR_I = [ADR_{initial}/(d-\zeta)]*[1-[(1+\zeta)^n/(1+d)^n]$.

Please cite this article as: Chaurey, A., Kandpal, T.C., Solar lanterns for domestic lighting in India: Viability of central charging station model. Energy Policy (2009), doi:10.1016/j.enpol.2009.06.047

Table 8
Impact of the annual escalation in kerosene price on daily rental values.

Sl. no.	ADR_l (Rs.)	$ADR_{initial}$ (Rs.)			
		$\zeta = 0.05$	$\zeta = 0.10$	$\zeta = 0.15$	$\zeta = 0.20$
1	4.25	3.07	2.10	1.37	0.85
2	4.00	2.88	1.97	1.29	0.80
3	3.75	2.70	1.85	1.21	0.75
4	3.50	2.52	1.73	1.13	0.70
5	3.25	2.34	1.60	1.05	0.65
6	3.00	2.16	1.48	0.96	0.60
7	2.75	1.98	1.36	0.88	0.55
8	2.50	1.80	1.23	0.80	0.50
9	2.25	1.62	1.11	0.72	0.45
10	2.00	1.44	0.99	0.64	0.40
11	1.75	1.26	0.86	0.56	0.35
12	1.50	1.08	0.74	0.48	0.30
13	1.25	0.90	0.62	0.40	0.25
14	1.00	0.72	0.49	0.32	0.20

are also expected due to learning effect and improved system designs of CCS.

4.2. *Emerging storage and lighting technologies*

In the charging station model the users of solar lantern would perhaps prefer longer hours of operation of the lantern in order to reduce the frequency of their visits to the CCS. The charging station operators on the other hand would desire that charging time for the battery be reduced so that more lanterns can be charged in a day. Both these requirements can be addressed by technological advancements that are taking place in storage as well as in lighting devices.

4.2.1. *Storage devices*

The desirable characteristics of an appropriate rechargeable battery for use in solar lanterns include (Lambert et al., 2000; Mukerjee, 2000): (a) good reliability under cyclic charge–discharge conditions, (b) low self-discharge and zero maintenance requirements, (c) high charging efficiency, (d) wide range of operating temperatures, (e) high volumetric and gravimetric energy densities, (f) low cost per watt-hour, (g) environmental safety and robust design, and (h) storage and use in any position and orientation.

Solar lanterns disseminated in India commonly use the valve regulated lead-acid (VRLA) batteries. Lithium-ion (Li-ion) and Nickel-Metal Hydride (Ni-MH) batteries are also being used in solar lanterns. Since Li-ion and Ni-MH batteries are routinely used in products such as portable computers, cordless appliances, telecommunication and medical equipment, the outcomes of technological advancements and cost reductions will benefit solar lanterns also.

4.2.2. *Lighting devices*

Solar lanterns already use CFLs that have higher efficacy as compared to incandescent bulbs while lasting longer (McKeown and Swire, 2008). One of the challenges of using CFL in solar lanterns has been the lack of quality control in locally manufactured CFLs. The mercury content in CFLs has also been a global concern that has led the lighting industry to switch to cleaner and more efficient light emitting diodes (LEDs). The advantages of LEDs that make them suitable for solar lanterns are reduced maintenance; ability to be dimmed, cold start capacity and operability at low voltages thereby reducing the size of battery and of PV module (Babu, 2008). The advancements in LED technology are expected to bring down their costs in terms of Rs. per Watt and give more lumen output per Watt thereby bringing down the cost of useful energy from LED lanterns.

New generation solar lanterns are, therefore, expected to provide longer duration of illumination per recharge of the battery, brighter illumination and reduced O&M requirements due to increased longevity of components.

4.3. *New and innovative financing and funding mechanisms*

Solar lantern is a clean lighting device that has the potential for providing benefits of lighting to millions of households that mostly use kerosene as a lighting fuel. As mentioned earlier, India alone has 67.6 million rural households that use kerosene for lighting, consuming about 2 billion litres of kerosene annually, estimated at an average monthly consumption figure of 2.5 l per household (Chaurey and Kandpal, 2007; Rehman et al., 2005). The annual subsidy burden is expected to be over Rs. 32 billion (Misra et al., 2005) for a subsidy of Rs. 24.81 per litre. It would also be worthwhile looking at the requirement of total subsidy if households were to switch to solar lantern as estimated in diffusion scenario discussed in Appendix 1. If 20 million rural households were to own solar lanterns and if all of them are able and willing to pay at least 10% of the capital cost of Rs. 3300 for a 7 W CFL lantern, then the one time subsidy burden would be to the tune of Rs. 59.4 billion. Alternately, to serve these 20 million households about 400,000 CCS would be required. If these CCS were to be set up with 100% capital subsidy support, one time amount of Rs. 57.8 billion would be required. On the other hand, if these 20 million households continue to rely on kerosene, then an amount of Rs. 9.46 billion would be required annually towards subsidizing kerosene. Thus, instead of subsidizing kerosene, if the government were to subsidize the diffusion of solar lanterns (either through ownership or rental mode) net saving to the national economy is expected on a lifecycle basis.

Each solar lantern has a potential to mitigate about 143 kg CO_2 annually by replacing 4 hours of usage of kerosene lamp daily (Chaurey and Kandpal, 2009). Twenty million users of solar lanterns can collectively abate 2.86 million tonne of CO_2 annually. The emerging markets for clean technologies could perhaps be a potential financing source, particularly for CCS model with opportunities for innovative business models as discussed further.

4.4. *Opportunities in expansion of charging stations*

The modular design of the CCS offers the advantage of need based capacity expansion of the charging station. The capacity can be enhanced with additional PV module(s) and/or any other renewable energy technology such as wind-electric generator, biomass gasifier based power-generating unit, etc. The CCS can thus function like a mini-utility in the village that can offer battery charging facilities for a multitude of applications such as mobile telephone charging, water purification, powering computers and television sets, etc. Besides, there are opportunities for introducing newer CCS designs. For example, a buffer battery bank that is charged first from the PV modules can be employed to charge the solar lanterns to offer flexibility to the user of bringing the lantern anytime of the day. A manually driven paddle charger can also be used to keep the buffer battery bank topped up in days of low sunshine. Such a charger is being developed by a few manufacturers and is currently under trial (Freeplay, 2008).

4.5. *Improved institutional support for assembly, servicing, O&M and quality control of central charging stations*

The CCS model has the potential to build and strengthen many institutions at the local level and at national level. Setting up of

Please cite this article as: Chaurey, A., Kandpal, T.C., Solar lanterns for domestic lighting in India: Viability of central charging station model. Energy Policy (2009), doi:10.1016/j.enpol.2009.06.047

central charging stations would require identifying, selecting and training entrepreneurs to operate and manage a charging station, while at the same time, undertaking servicing of solar lanterns in terms of minor repairs and replacements of parts. So far, this activity is usually undertaken at the project level where entrepreneurs are selected and trained within the project boundary itself. However, if national level programmes are launched to develop the institution of charging station entrepreneurs, initiatives such as Lighting a Billion Lives and Lighting Africa would provide ample livelihood opportunities to such trained entrepreneurs. At the same time, it would also help ensure quality control in the components used and services provided.

The CCS model also offers a platform for linking and synergizing the initiatives and commitments of the NGOs, community based organizations (CBOs), local governments, private sector and donor agencies towards socio-economic development of the communities using lighting as a means for facilitating and advancing their initiatives. Health services, Information and Communication Technology based educational services, water purification services, etc. can be provided to the communities by expanding the capacity of the solar lantern charging stations in future. It also provides a market for financing and micro-financing institutions to help the potential buyer of solar lantern, while at the same time, enabling the entrepreneurs and service providers to initiate and expand businesses of providing lighting products and services.

5. Conclusions

The ownership and fee-for-service/rental models for dissemination of solar lanterns in India have been evaluated in the paper. Also the viability of central charging model for renting solar lanterns to households that use kerosene for lighting has been assessed. The results have indicated that a CCS is not viable even with 100% capital subsidy support if the households were to compare renting vs. owning the solar lantern and were unwilling to pay a daily rental that is more than the effective daily cost of owning the solar lantern. The fraction of capital subsidy required for filling the gap between the daily rental for the lantern that the user would be willing to pay and the amount that the CCS entrepreneur would require to profitably run the business has also been estimated. The likely effect of kerosene price escalation on the acceptable daily rental to the CCS owner has also been studied. The study highlights that:

(a) The daily cost of owning a 7 W CFL lantern to the user is Rs. 1.88 that is also the maximum amount the user would be willing to pay for renting the lantern daily. This amount is Rs. 0.95 for a 2.5 W LED lantern. The corresponding values are Rs. 1.32 and 0.56, respectively, if the user owns the lanterns and pays a daily fee to the CCS owner for recharging the battery.

(b) The minimum daily rental required by an entrepreneur to viably own and operate a CCS with 50 numbers of 7 W CFL lanterns is estimated at Rs. 4.06. Its value is Rs. 3.33 for 2.5 W LED lanterns if the CCS entrepreneur owns lanterns. In case the users own the lanterns, the daily recharge fee would be Rs. 3.02 and 2.60 for the CFL and LED based lanterns, respectively.

(c) For a daily rental of Rs. 2.00 per lantern, a CCS with 50 numbers of 7 W CFL lanterns becomes viable provided 99% capital subsidy is provided to the entrepreneur. The corresponding value is Rs. 1.93 if the CCS owner does not own the lanterns, and hence does not incur any costs towards their purchase and maintenance.

(d) The CCS can run viably without any capital subsidy support if the user is wiling to pay a daily rental of Rs. 4. For the case of users owing the lanterns the corresponding value of recharge fee is Rs. 2.98.

(e) The initial value of acceptable daily rental to the CCS owner could be reduced to Rs. 2.88 from Rs. 4 if an annual fuel price escalation of 5% is taken into consideration. The subsidy requirement would however increase.

Appendix 1. : estimation of potential of diffusion of solar lanterns and subsequent economies of scale

Theoretically, all rural households using kerosene for lighting (67.6 million) could switch to solar lanterns. However, this may not be the case due to many factors that influence such a decision. Access to supplier and/or availability of solar lanterns, affordability and willingness to pay by the households, access to sites with good solar radiation and propensity to use are few of the most critical factors for adoption of solar lanterns. The potential of solar lantern diffusion can therefore be estimated as (Chaurey and Kandpal, 2009)

$$\text{SolarLantern}_{potential} = N_0 \mathrm{f}_{pp} \mathrm{f}_{sr} \mathrm{f}_{pb}, \tag{10}$$

where N_0 represents the number of households using kerosene for lighting (67.6 million) and f_{pp} the fraction of N_0 that can afford to pay the rent for using a solar lantern. Of these, only a fraction f_{sr} fall in the region that receives sufficient solar radiation. Finally, of all the households that can pay the rent and have access to sufficient solar radiation, only a factor f_{pb} actually have propensity to use the solar lantern.

A typical rural household in India incurs 10% of its monthly per capita expenditure (MPCE) on fuel and light of which 80% is spent on lighting. Practically, this entire expenditure is likely to be on lighting as 84% of rural household depend on firewood, agricultural residues and dung cake for cooking that presumably are collected free of cost. Thus the household that wishes to use a solar lantern can spend at least upto 10% of its MPCE on paying the rent of solar lantern. In other words, monthly collective income of the household should be 10 times that of the monthly rental for the solar lantern. A CCS can run viably if households are willing to pay a rent of Rs. 4 per day or Rs. 120 per month (Table 7). For a household to pay a monthly rent of Rs. 120, the monthly collective expenditure ability of its five members should be 10 times that of the monthly rent it is going to pay, i.e. Rs. 1200. In other words, the monthly expenditure ability of its individual member should at least be Rs. 240. Such a household would fall in the MPCE class of Rs. 235–270 in the classification of National Sample Survey Organization (NSSO). There are about 62 million rural households that belong to the MPCE class of Rs. 235–270 and above who use kerosene for lighting (Chaurey and Kandpal, 2009) and would be prospective users of solar lantern if available on rent.

As discussed earlier, not all of the 62 million households estimated above will have access to solar radiation. About 25% of all households using kerosene for lighting in the country are located in the regions that do not have access to adequate solar radiation and hence they will not be able to use solar lanterns effectively. Thus, the potential for solar lantern diffusion would be around 46 million taking f_{sr} to be 0.75. Even if about half of these 46 million households show propensity to buy an SHS, the potential of solar lanterns utilization in the country would be in the range 20–25 million.

From the relationship of income distribution (expressed as MPCE) and percentage of households using kerosene across several states in India (Table 9) it may be noted that the states having higher income distribution have lower percentage of their households using kerosene. This observation is significant as it

Table 9
Percentage rural households using kerosene for lighting and income distribution of rural households across various states in India (Source: NSSO, 2008).

State/group of states/union territory	Estimated number of rural households	Percentage of rural households using kerosene	Average monthly per capita expenditure (MPCE)
Orissa	7,264,000	69.4	380
Chhatisgarh	3,554,300	20.6	422
Tripura	646,900	45.9	452
Madhya Pradesh	962,6500	32.6	469
Andhra Pradesh	14,813,700	13.3	493
Jharkhand	3,972,300	62.2	495
Bihar	14,963,200	88.2	532
North-Eastern States	1,807,000	26.8	545
West Bengal	14,335,000	62.1	552
Gujarat	7,127,700	15.7	565
Karnataka	7,602,200	11.6	572
Assam	5,786,600	67	573
Uttar Pradesh	24,563,100	71.8	584
Manipur	299,900	12.8	589
Haryana	311,100	3.5	633
Tamil Nadu	9,713,400	9.6	651
Rajasthan	7,687,500	44.8	660
Maharashtra	11,945,900	27.2	666
Meghalaya	382,000	25.4	670
Punjab	3,451,200	11	682
Arunachal Pradesh	135,900	16.8	700
Himachal Pradesh	1,260,200	1.7	731
Kerala	5,715,800	12.8	794
Union Territories	226,700	3.6	908
Jammu and Kashmir	1,017,000	1.1	985
All India	160,868,100	42.3	553

indicates that rural population depending extensively on kerosene have perhaps lower incomes or expenditure capabilities and therefore might prefer rental to ownership model and can be helpful in identifying the states where diffusion of solar lanterns through CCS might be more successful.

References

Babu, T.A., 2008. LEDs: Bring a new era in lighting. Electronics for You. September. pp. 132–144.

Chaurey, A., Kandpal, T.C., 2007. Feedback on the use of solar home systems: results of a questionnaire based pilot survey. SESI Journal 17 (1–2), 38–53.

Chaurey, A., Kandpal, T.C., 2009. Carbon abatement potential of solar home systems in India and their cost reduction due to carbon finance. Energy Policy 37, 115–125.

Development Marketplace, 2008. 〈http://www.developmentmarketplace.org/〉. Website of Development Marketplace Accessed August 2008.

DNES, 1992. Annual Report 1992–93. Department of Non-conventional Energy Sources. Government of India.

Dutt, G.S., 1994. Illumination and sustainable development—Part I: technology and economics. Energy for Sustainable Development 1 (1), 23–35.

Dutt, G.S., Mills, E., 1994. Illumination and sustainable development—Part II: implementing lighting efficiency programmes. Energy for Sustainable Development 1 (2), 17–27.

Freeplay, 2008. 〈http://www.freeplayenergy.com/products〉. Website of Freeplay Energy Plc Accesses on October 2008.

Gaur, V., Marcus, S.J., 2008. From darkness to light—a survey of solar lanterns in India. The Solar Quarterly 1 (1), 63–73.

GNESD, 2009. 〈http://www.gnesd.org〉. Website of Global Network on Energy for Sustainable Development. Accessed January 2009.

LaBL, 2009. 〈http://labl.teriin.org〉. Website of Lighting a Billion Lives. Accessed May 2009.

Lighting Africa, 2008. 〈http://lightingafrica.org/docs/Tanzania_Qualitative_Market_Assessment.pdf〉. Website of Lighting Africa Initiative of the World Bank Group.

Lambert, D.W.H., Holland, R., Crawley, K., 2000. Appropriate battery technology for a new, rechargeable, micro-solar lantern. Journal of Power Sources 88, 108–114.

Lucas, C., 2008. Access to Solar Photovoltaic lanterns in rural India: Report on TERI LaBL campaign in Assam, West Bengal and Rajasthan. Accessed through TERI. (Personal communications).

McKeown, A., Swire, N., 2008. Strong growth in compact fluorescent bulbs reduces electricity demand. Email updates from Worldwatch Institute. 〈http://worldwatch.org/donate〉. Accessed October 2008.

Misra, N., Chawla, R., Srivastava, L., Pachauri, R.K., Petroleum pricing in India—balancing efficiency and equity. TERI 2005. New Delhi.

MNRE, 2009. 〈http://mnre.gov.in/〉. Website of Ministry of New & Renewable Energy, Government of India. Accessed May 2009.

Mukerjee, A.K., 2000. Comparative study of solar lanterns. Energy Conversion & Management 41, 621–624.

Mukhopadhyay, K., Sensarma, B., Saha, H., 1993. Solar PV lanterns with centralized charging station—a new concept for rural lighting in developing countries. Solar Energy Materials and Solar Cells 31, 437–446.

NSSO, 2008. National Sample Survey Organisation. Household Consumer Expenditure in India. NSS Report no. 527. Ministry of Statistics and Programme Implementation. Government of India.

PowerLine, 2009. An expensive option—but economies of scale could drive down solar energy costs. 13(8), 68–70.

Rehman, I.H., Malhotra, P., Pal, R.C., Singh, P.B., 2005. Availability of kerosene to rural households—a case study for India. Energy Policy 33 (17), 2165–2174.

REN21, 2009. Renewables Global Status Report: 2009 Update (Paris: REN21 Secretariat).

Rentzing, S., 2008. Premature degradation. New Energy 5, 66–69.

Roy, J., Jana, S., 1998. Solar lanterns for rural households. Energy 23 (1), 67–68.

Rubab, S., Kandpal, T.C., 1996. Financial evaluation of SPV lanterns for rural lighting in India. Solar Energy Materials and Solar Cells 44, 261–270.

TERI, 2004. Women as solar power entrepreneurs—a pilot project in the Sunderbans. The Energy and Resources Institute Report.

TERI, 2008. Personal communication and visit to LaBL project site.

Velayudhan, S.K., 2003. Dissemination of solar photovoltaics: a study on the government programme to promote solar lantern in India. Energy Policy 31, 1509–1518.

Please cite this article as: Chaurey, A., Kandpal, T.C., Solar lanterns for domestic lighting in India: Viability of central charging station model. Energy Policy (2009), doi:10.1016/j.enpol.2009.06.047