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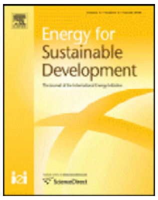

Evaluation of various energy devices for domestic lighting in India: Technology, economics and CO_2 emissions

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ABSTRACT

Four out of five people without electricity live in rural areas of developing countries, mainly in South Asia and sub-Saharan Africa. Most of these households use kerosene lamps for lighting. The light outputs of these devices are very poor and vary from about 10 to 100 lumens, depending on the type of lamps and wicks. The paper compares the technology, economics and CO_2 emissions of kerosene-based lamps with modern bio-energy systems and solar photovoltaics. Light output, luminous efficacy and energy consumption are used for comparing the technical parameters. Economics is expressed in terms of the cost of useful energy (cost per 1000 lumen hours), determined from the annualized life cycle cost of the systems. Fuel consumption rates are used to determine CO_2 emissions of all the devices. This study reveals that efficient electric lighting provides higher light levels and low energy consumption as well as low CO_2 emissions. In the absence of grid electricity, distributed renewable energy systems such as solar photovoltaics (at individual house level) and modern bio-energy systems are better options for providing good quality and reliable lighting in rural areas compared to traditional kerosene-based lighting. Moreover, these renewable energy systems as well as grid-based electricity systems also reduce CO_2 emissions.

Introduction

Thomas Edison's statement that "we will make electricity so cheap that only the rich will burn candles" is true to a great extent for the industrialized world, but he did not anticipate the plight of 1.6 billion people or 26% of total world population, who still lack access to electricity (Mills, 2005; World Energy Outlook, 2004). More than 99% of people without electricity live in developing countries and four out of five live in rural areas (World Energy Outlook, 2004). Of these, 15% of urban households and 48% of rural households were without electricity as of the year 2002 (World Energy Outlook, 2004). More than 80% of the people who currently have no access to electricity are located in South Asia and sub-Saharan Africa (World Energy Outlook, 2004). The lowest electrification access in the world is sub-Saharan Africa where only 24% of the population has access to electricity. More than 500 million Africans are still without access to electricity (World Energy Outlook, 2004). Electricity access to the population in the year 2002 for the different regions is presented in Table 1.

Energy scenario in India

Rural population in India constitutes almost 72% (740 million) of its total population (Census Report, 2001). At present, 80% of the total villages in the country has access to grid electricity; leaving a balance of approximately 125,000 villages still waiting to be connected to the grid (MNRE, 2009). Out of this, 25,000 are difficult ones where extension of grid is neither technically possible nor economical (MNRE, 2009). Today, the rural electrification programs within the different states of India are widely diverse. Eight States (Andhra Pradesh, Goa, Haryana, Maharashtra, Kerala, Punjab, Tamil Nadu and Nagaland) have achieved 100% village electrification, which constitutes only 18% of the villages of the country. Whereas states with 80% or more households yet to be electrified (Bihar, Jharkand, Assam, Orissa, Uttar Pradesh, West Bengal) constitute 43% of country's total rural households (MoP, 2007). Though village electrification has covered 80% of the total villages of the country, only 43.5% of the rural households have access to electricity. The total electricity generation installed capacity is 141,500 MW; the energy shortage and peak demand shortage are 9.3% and 13.9%, respectively (MoP, 2007). These shortages are one of the reasons for poor quality and regular blackout and brownout in electricity supply in rural areas and in particular the evening time. Illumination represents 10–20% of electricity used in most countries and sometimes more in developing countries (Balachandra and Shekar, 2001). The electricity shortage can be reduced to a great extent by conserving energy through efficient alternatives (Balachandra and Shekar, 2001).

Electricity and kerosene are mainly used for lighting in both urban and rural areas. Kerosene is primary fuel for lighting for 43.3% and electricity for 55.8% of Indian households (Census Report, 2001). Seventy-eight million rural households and 7 million urban

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Table 1
Electricity access in the year 2002: regional aggregates (World Energy Outlook, 2004).

Region	Electrification access (%)	Population without electricity (million)	Population with electricity (million)
North-Africa	93.6	9	134
Sub-Saharan Africa	23.6	526	162
China and East Asia	88.1	221	1639
South Asia	42.8	798	598
Latin America	89.2	46	382
Middle East	91.8	14	158
Transition economy and OECD	99.5	7	1484
World	73.7	1623	4556

Table 2
Distribution of households in India by source of lighting (Census Report, 2001).

Sources of lighting	Total households		Rural households		Urban households	
	Numbers	(%)	Numbers	(%)	Numbers	(%)
Electricity	107,209,054	55.8	60,180,685	43.5	47,028,369	87.6
Kerosene	83,127,739	43.3	76,896,701	55.6	6,231,038	11.6
Solar energy	522,561	0.3	394,425	0.3	128,136	0.2
Other oil	184,424	0.1	146,165	0.1	38,259	0.1
Other forms of energy	305,308	0.2	227,210	0.2	78,098	0.1
No lighting	614,849	0.3	426,373	0.3	188,476	0.4
Total	191,963,935	100.0	138,271,559	100.0	53,692,376	100.0

households depend on kerosene or other energy sources besides electricity for lighting in India (Bhattacharyya, 2006). Distribution of households by sources of lighting is presented in Table 2. The other aspect of rural household lighting in India is that even in the electrified households, people continue to depend mainly on kerosene for lighting due to poor quality and regular load-shedding of electricity supply. According to one estimate, about 65% of the households in electrified villages do not receive the benefits of electricity even now (Rehman et al., 2005). This is both on account of the inability of households to afford electricity connections as well as low demand on account of poor reliability and quality of the existing grid supply (Rehman et al., 2005). The total kerosene consumption in India during 2000–2001 was estimated at around 11.5 MT, of which about 60% was for rural areas (Rajvanshi, 2003; Rehman et al., 2005). In rural areas, 1.2% rural households use kerosene for cooking. Thus, the primary use of kerosene in rural areas is for lighting (Rehman et al., 2005). The kerosene distribution systems in the country are at present subsidy based and employ a supply driven distribution approach to facilitate its access to the poor (Rehman et al., 2005). The government spent INR 9670[1] million as subsidy in kerosene supplied for domestic use through the public distribution system in 2006–2007 (MoPNG, 2007). It is also not feasible for government to withdraw this subsidy completely due to its political compulsions; rather the amount of subsidy will increase with the increase of international crude oil price.

Energy devices for domestic lighting

There is a wide variety of light sources like wax candles, oil lamps, ordinary kerosene wick lamps, pressurized kerosene lamps, biogas mantle lamps, incandescent lamps (IL), fluorescent lamps (FL), compact fluorescent lamps (CFL), white light emitting diode lamps (WLED), etc. A comparative analysis of all these different lighting sources is presented in Table 3. According to most studies, ordinary kerosene lamps like kerosene wick lamps and hurricane lanterns are the most common type of fossil fuel-based lighting source in developing countries (Mills, 1999). The light output of kerosene lamps varies from about 10 to 100 lumens depending on the type of lamps and wicks. The efficiencies of illumination vary from 100 lumens/W to below 1 lumen/W (Mills, 2005). The levels of illumination provided by flame-based lamps are much lower than with modern electric lighting. The result is a substantial level of primary energy use for very little lighting "service" (Dutt, 1994). A reasonable lighting level (illuminance), in the range of 100 to 200 lux (lumen/m^2), suggests that India's 77 million rural households with kerosene lamps do not receive anywhere near adequate illuminance.

Renewable energy systems for domestic lighting

Decentralized renewable energy systems have already been proven as a better option for rural electrification in different parts of world. These systems may be setup as a stand-alone system for a single household or combined for a cluster of households. These renewable energy systems include biogas, solar photovoltaics, biomass gasifiers, small wind energy systems, micro and pico hydro, etc. However, for some of the systems, resource availability is a critical factor, thereby limiting their suitability to specific locations (Rubab and Kandpal, 1997). Wind energy systems are limited to the wind availability at a particular location. Biomass gasifier-based systems are not appropriate for lighting a single household; it is useful for a cluster of households. Table 4 provides the installed capacity of various decentralized renewable energy systems to meet different energy needs in India. The Ministry of New and Renewable Energy Sources (MNRE) is the nodal Ministry of the Government of India for implementation of the various renewable energy systems throughout the country.

The paper evaluates the technical and economical feasibility issues of traditional kerosene-based lamps and currently available renewable energy-based lighting systems. The present study considers kerosene-based lamps, modern bio-energy-based systems and solar photovoltaic-based systems for providing light to rural households. The economics of operation, i.e., the cost of useful energy (illumination) based on annualized life cycle cost (ALC) of all these systems, are calculated. These calculations are based on details available in the literature in the form of project reports, catalogues, etc. Although realistic costs have been used in the analysis, these parameters are indicative; the results are expected to vary among manufacturers and locations. Based on these costs, the possible options are identified for providing good quality and reliable lighting in rural areas. The paper also evaluates the CO_2 emissions from various lighting systems.

Different options for domestic lighting

Kerosene-based lamps

Illumination from kerosene-based devices follows the principle of incandescence. In the incandescent lamps, most energy is lost in the form of waste heat. Moreover, combustion processes produce unwanted air pollutants. Smoke from kerosene lamps is responsible for respiratory infections, lung and throat cancers, serious eye infections, cataracts as well as low birth weights (Schare and Smith, 1995). In India, mainly four types of kerosene lamps are in use: the chimneyless primitive wick lamps (commonly called as *chirag* or *diya*), kerosene lamps (with chimney), hurricane lantern and pressurized kerosene lamps (Mills, 1999; Rubab and Kandpal, 1997). The following section provides details of the different kinds of kerosene-based lamps.

Kerosene wick lamps

Kerosene-based devices like kerosene wick lamps, hurricane lanterns are the most common type of kerosene fuel-based lighting in developing countries (Mills, 1999). Experimental results reveal that for most common kerosene-based lamp the light output is 76 lumens

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[1] 1 US $ = INR (Indian Rupees) 49.62 on May 13, 2009.

Table 3
Comparative analysis of different lighting sources (Mills, 1999; Dishna et al., 2005; Rubab and Kandpal, 1997).

Type of lamps	Fuel consumption	Power rating (W)	Luminous flux (lumen)	Efficacy (lumens/W)	Life (h)
Candle	5.5–7.2 (g/h)	55–72	1–16	0.02–0.22	1
Kerosene wick lamp	0.02–0.05 (l/h)	200–488	10–100	0.05–0.21	5500
Petromax	0.06–0.08 (l/h)	563–813	220–1300	0.39–1.60	7500
Noorie[a]	0.05 (l/h)	513	1250	2.44	7500
LPG lamp	28–34 (g/h)	350–425	330–1000	0.94–2.35	7500
Biogas mantle lamp	0.1–0.2 (m^3/h)	693–1385	330–1300	0.48–0.94	7500
IL[a]	100 (W)	100	1200	12	1200
FL[a]	48 (W)[b]	48	2450	51	8000
CFL[a]	7 (W)	7	370	53	8000
WLED[a]	1 (W)	1	40	40	50,000

[a] Noorie, energy efficient kerosene-based lamp; IL, incandescent lamp; FL, (linear) fluorescent lamp; CFL, compact fluorescent lamp; WLED, white light emitting diode.
[b] FL T8 36 W lamp (CHLI36/54) rated light output 2450 lumens. Here, the ballast energy consumption is considered 12 W. Thirty-six watt triphosphor lamps generate considerably more light, typically around 3350 lumens. However, these efficient triphosphor lamps are not commonly used in India at present but would be a good option in the future.

and the kerosene consumption is 21.6 ml/h (Mukherjee et al., 1998). The light output from kerosene lamps is very poor. The efficacy of kerosene hurricane lamp varies from 0.05 to about 0.21 lumens/W (Mills, 1999). These lamps are highly inefficient in terms of fuel consumption and light output.

Petromax

Pressurized kerosene lanterns (Petromax) work on the principle of evaporation of kerosene in a preheated fuel tube, mixing of this kerosene vapor with air and the mixture being combusted to produce high flame temperatures. This high-temperature non-luminous flame heats the mantle to produce light (Rubab and Kandpal, 1997). The light output of a Petromax at fully pressurized condition is around 1300 lumens (Mills, 1999; Rubab and Kandpal, 1997). The efficacy of these lamps is 0.39–1.60 lumens/W (Mills, 1999). These lamps are superior to traditional kerosene lamps in terms of efficacy. However, this device produces low frequency noise due to the pressurized combustion, which could be undesirable.

Noorie

Nimbkar Agricultural Research Institute (NARI), India developed an efficient lamp called *Noorie* (Rajvanshi, 2003). The efficacy of the device is high compared with the other devices by rightly tuning the combustion process and the necessary adjustments on the mantle. The efficacy of this lamp is 2.44 lumens/W, much higher than other kerosene-based lamps. It is also a pressurized mantle lantern. It produces light by heating thermo-luminescent mantles with an output of 1250–1300 lumens (Mills, 1999; Rajvanshi, 2003). It produces light output equivalent to that of Petromax lamps but with only 60% of the kerosene consumption and about one-third the pressure used in them (Rajvanshi, 2003).

Table 4
Decentralized renewable energy system installations in India as of 2009 (MNRE, 2009).

Source/system	Cumulative installed capacity[a]
Solar photovoltaic systems	
• Solar street lighting systems	70,474 nos.
Home lighting systems	450 000 nos.
• Solar lanterns	730 000 nos.
• Solar photovoltaic power plants	8.01 MW_p[b]
Modern bio-energy systems	
• Biomass gasifiers	105.46 MW
• Family type biogas plants	4.13 million
Wind energy	
• Aero generator/hybrid systems[c]	0.89 MW_{eq}[d]

[a] As on March 31, 2009.
[b] MW_p, megawatt peak.
[c] Wind farms are not included here since they supply electricity to the power grid.
[d] Aero generators are also used for water pumping apart from battery charging and the rating of these pumps are expressed in terms of MW_{eq} (megawatt equivalent).

Traditional kerosene wick lamps, Petromax and Noorie, are considered for evaluation as kerosene-based domestic lighting in this study. The input parameters for evaluation are based on market prices, manufacturers' catalogues and various reports and are presented in Table 5.

Modern bio-energy systems

Modern bio-energy-based systems like biogas and biomass gasifier are already proven as a good option for meeting the cooking, lighting, electrical and heating energy needs of households in different parts of the world (Dasappa et al., 2004; Rajvanshi, 2003). Biogas systems include the traditional biogas-based lamps for lighting and biogas systems coupled with an engine for electricity generation. Biogas-based mantle lamps are useful for single households and biogas-based electricity systems are suitable for a cluster of households. However, resource availability is a critical factor that decides its suitability for a single household or for cluster of households.

Biomass gasifier systems have been widely used for rural electrification (Ghosh et al., 2004; Mukhopadhyay, 2004; Nouni et al., 2007). Various kinds of biomass, agro-residue, etc. may be used as feedstock for this kind of system. This is useful for a cluster of households in a village. This system may also be coupled with small scale industrial load of villages apart from providing lights to the household. Application specific criteria are required for widespread deployment of biomass gasifiers and to meet the need of the end user (Ghosh et al., 2006).

Biogas-based lighting systems

Biogas is produced by anaerobic digestion of biodegradable wastes of a village; cattle dung is most commonly used feedstock. Biogas

Table 5
Input parameters for kerosene lamps.

	Kerosene wick lamp	Petromax	Noorie
Unit lamp cost (INR)	100	325	450
Annual maintenance cost (INR)	20	50	50
Fuel cost (INR/l)[a]	35	35	35
Life of the system (years)	5	5	5
Kerosene consumption (ml/h)	21.6	80	50
Lamp power rating (W)[b,c]	218	806	504
Light output (lumens)	76	1300	1250
Daily operational hours (h)	4	4	4

[a] The open market cost of kerosene) is INR 35/l and at public distribution system (PDS) it is INR 9.50/l (as on December 27, 2008). However, the PDS kerosene is available only to people below the poverty line and the supply of this kerosene is very much irregular. So in this calculation, the open market cost of kerosene is considered.
[b] Power rating for non-electrical-based lighting systems is calculated by multiplying the specific fuel consumption (f_C), density (ρ) and calorific value (CV) of the fuel. The relation can be written as;$P(watt) = f_C\left(\frac{litre}{s}\right) \times \rho\left(\frac{kg}{litre}\right) \times CV \times \left(\frac{Joule}{kg}\right)$.
[c] The calorific value and density of kerosene are considered to be 45 MJ/kg and 806 g/l.

contains around 55–65% of methane, 30–40% of carbon dioxide and small quantities of hydrogen, nitrogen, oxygen and hydrogen sulfide. The calorific value of biogas is around 23 MJ/m^3 at 60% methane. Biogas is a versatile source of energy for cooking, lighting and shaft power applications. Over 4.13 millions biogas plants of various capacities have been installed in various parts of India till March 2009 mainly to meet cooking and lighting energy needs (MNRE, 2009). Research and development efforts to extend the use of biogas plants to feed stock other than animal dung such as leaves and rural agro-residues have been successfully demonstrated by the Centre for Sustainable Technologies, Indian Institute of Science in the field (Chanakya et al., 2004, 2009).

Biogas mantle lighting systems

A mini-biogas digester of 0.5 m^3 capacity can produce sufficient biogas for 4 h of lamp use (Jash and Basu, 1999). So a biogas plant of 1 m^3 can supply sufficient biogas to run two biogas mantle lamps for 4 h. This kind of digester is useful for small family units, exclusively for lighting purposes. The operation costs include the labor cost for daily feeding of cattle dung into the plant. The annual maintenance cost of the system is low. Lighting is the most profitable end-use for biogas followed by cooking and motive power at the prevailing prices of alternative energy sources (Sinha and Kandpal, 1990). Biogas lamps are made of rare earth incandescent mantles. The average light output from biogas lamps is about 600 lumens and the efficacy varies from 0.48 to 0.94 lumen/W (Mills, 1999; Rubab and Kandpal, 1997). The input parameters used for financial evaluation based on market prices and different project reports are presented in Table 6.

Biogas-based electricity systems

Biogas can be utilized for power generation after drying and cleaning of the gas, using 100% biogas engines or dual-fuel engines (biogas + diesel). Biogas plants connected to dual-fuel engines for electricity generation have already been successfully implemented in many villages of South India (Rajabapaiah et al., 1993). Pilot scale 100% biogas engines in the 300–500 W range, capable of efficient operation, are now available in India (Kapadia, 2006). However, it still needs more time for field application. Thus, biogas-based electricity generation system (dual fuel mode) is a useful way to provide domestic lighting in rural areas. This kind of system is more useful for clusters of households. The input parameters used for financial evaluation based on market prices and various project reports for dual-fuel-based biogas systems are presented in Table 7.

Biomass gasifier-based lighting systems

Biomass gasifiers carry out thermo-chemical conversion of biomass through the process of oxidation and reduction under sub-stoichiometric conditions. Biomass gasifiers, as a source of combustible gas for energizing internal combustion engines, have been in existence for almost a century. During the Second World War, gasifiers were used extensively. However, shortly after the war most gasifiers were decommissioned because of widespread availability of inexpensive petroleum fuels. The energy crisis of the 1970s brought a renewed interest in gasifiers. Gasifiers are classified into different designs based on the direction of flow of the fuel bed and the gas. A downdraft gasifier, in which fuel and air move downward, is widely used for power generation because it generates combustible gas with low tar content. This approach is now popular in India. Developmental work at Indian Institute of Science, Bangalore, India on wood gasifier resulted in a design with an open top design, with air entering both from the top and through air nozzles on the side (Dasappa et al., 2004).

Table 6
Input parameter for biogas mantle lighting systems.

Capacity of the biogas plant (m^3)	1
Cost of the biogas plant (INR)	6000
Annual maintenance cost (INR)	5% of capital cost
Mantle lamp cost (INR)	10
Life of the plant (years)	20
Life of the mantle (h)	300
Daily operational hours (h)	4
Fuel cost (INR)	Nil
Daily labor cost for feeding (INR)[a]	5
Each lamp power rating (W)[b]	799
Number of lamps	2
Light output from each lamp (lumens)	600

[a] The cost for 8 man-hours (1 day) is INR 80/-. It is considered that the time requirement for feeding the material into the plant is 0.5 h. So the cost of feeding per day is INR 5/-.

[b] The biogas consumption in each lamp is 0.125 m^3/h. The calorific value and density of biogas are considered 23 MJ/m^3 and 1.112 kg/m^3, respectively.

Table 7
Input parameter for biogas-based electricity systems.

Capacity of the biogas plant (m^3)	50
Cost of the biogas plant excluding engine (INR)	372,000
Engine capacity (7 HP) (W)	5595
Engine genset cost (INR)	55,000
Effective electrical output (W) (10% distribution loss)	5035.5
Life of the plant (years)	20
Working life of the engine (years)	3.5
Number of overhaulings of the engine	3
Life of the engine after overhauling (years)	14
Cost of every overhauling (INR)	4350
Daily operational hours (h)	4
Dung required (kg/h of operation)	70
Diesel requirement (ml/h of operation)[a]	0.28
Fuel (biogas) cost (INR)	Nil
Dung delivered cost (INR/kg)	0.10
Diesel cost (INR/l)[a]	35
Labor wage rate (INR/h)	10
Repair and maintenance cost (INR/h of operation)	1
Engine oil change required after use of operation (hrs)	500
Engine oil cost for every change (INR)	500
Each lamp power rating (W)	11
Number of lamps	458
Light output from each lamp (lumens)	900
Lamp life (burning hours)	8000
Lamp cost (INR)	120

[a] We assume dual-fuel biogas-diesel engines, with 20/80 biogas to diesel consumption.

The total installed capacity of biomass gasifiers in India is 105 MW (MNRE, 2009). In India, there are many biomass gasifier-based projects running successfully from a small capacity (5 kW) to large capacities (1 MW) (MNRE, 2009). The initial cost of the system is high; however, operation cost is low because gasifiers are currently coupled with gas engines in place of the dual fuel mode of operation used earlier and fuel is locally generated biomass, with no diesel consumption. The input parameters based on market prices and various project reports for financial evaluation are presented in Table 8.

Table 8
Input parameter for biomass gasifier systems.

System capacity (kW)	10
Gasifier rating (kg/h)	14
System cost (excluding engine) (INR)	700,000
Engine cost (INR)	200,000
Annual maintenance cost (INR/kWh)	1.50
Fuel cost (INR/kg)	1.50
Fuel consumption (kg/h)	14
Life of the plant (years)	15
Life of the engine (years)	7.5
Life of the lamp (burning hours)	8000
Daily operational hours (h)	4
Electrical output from gasifier (W) {(20% in-plant consumption)}	8000
Useful electrical output at end use point (W) {(10% as T & D loss)}	7200
Each lamp rating (W)	11
Number of lamps (CFL)	655
Light output from each lamp (lumens)	900

Solar photovoltaic-based systems

Solar photovoltaic technology enables the direct conversion of sunlight into electricity. Photovoltaic systems have emerged not only as useful power sources for applications such as lighting, water pumping, etc. but also in meeting the electrical energy needs of villages (Nouni et al., 2006; Rubab and Kandpal, 1996). The Ministry of New and Renewable Energy Sources, Government of India has been implementing solar photovoltaic programs over the last two decades (MNRE, 2009). The Ministry has given emphasis to photovoltaic lighting systems mainly in rural and remote areas of the country. Photovoltaic systems under this program include solar lighting systems such as solar lanterns, solar domestic lighting systems, solar street lighting systems and village level off-grid photovoltaic power plants.

Solar lanterns

A solar lantern is designed as a viable alternative to traditional kerosene-based hurricane lamps (Mukerjee, 2007). A solar photovoltaic-based lantern as a lighting system consists of a solar module, lamp (CFL: 7 W, 4 pin type), battery and a control unit. The battery is charged by the electricity generated by the solar module in day time and at night time it discharges the electricity through a lamp to provide illumination. The batteries used are usually maintenance free lead acid type. The lantern is essentially a portable lighting system suitable for indoor and outdoor lighting. The light output from a solar lantern is much more than that of a kerosene lamp. The technical features of solar lanterns are presented in Table 9.

Solar domestic lighting systems

A solar domestic lighting system consists of a solar module, lamps (CFL: 9 W/11 W; 2 or 4 pin type), a battery and a control unit. This kind of system is used for indoor lighting and the system size varies according to the number of lamps connected. Normally, two lamps are connected in each system. The batteries are tubular low maintenance lead-acid type. The technical features of solar domestic lighting systems are presented in Table 9.

Table 9
Technical specifications of photovoltaic lighting systems.

Photovoltaic lighting systems	Specifications	Light output
Solar lantern	Solar module: 8–14 Wp Battery: 12 V–7 AH Operation: 4 h Lamp (CFL): 7 W (4 pin type) Number of lamp: 1 Battery: 12 V–7 AH Operation: 4 h Lamp (CFL): 7 W (4 pin type) Number of lamp: 1	370 ± 5% lumens
Solar domestic lighting systems	Solar module: 37 Wp Battery : 12 V–40 AH Operation : 4 h Lamp (CFL): 9 W (2 or 4 pin type) Number of lamp: 2 Battery : 12 V–40 AH Operation : 4 h Lamp (CFL): 9 W (2 or 4 pin type) Number of lamp: 2	600 ± 5% lumens
WLED-based solar home lighting systems[a]	Solar module: 10 Wp Battery: 12 V–7 AH Operation: 4 h Lamp (LED): 2.5 W (33 LEDs cluster) Number of lamps: 2 Battery: 12 V–7 AH Operation: 4 h Lamp (LED): 2.5 W (33 LEDs cluster) Number of lamps: 2	150 ± 5% lumens

[a] Surja Bijlee, Solar Energy Lantern; http://www.suryabijlee.com/.

WLED-based solar home lighting systems

The solid-state white light emitting diode (WLED)-based solar photovoltaic systems are slowly becoming accepted and have good prospects for rural electrification (Mills, 2005; Sebitosi and Pillay, 2007). LEDs have now come up as an energy-efficient alternative to CFL at low illumination levels. The life of this kind of lamp can be very high, e.g., 50,000 operation hours. This technology is different from other lighting technologies with a continuing trend toward increasing light output, declining costs per unit of output and rising efficiencies (Mills, 2005; Sebitosi and Pillay, 2007). The technical features of WLED-based solar home lighting systems are presented in Table 9.

Solar lanterns, solar domestic lighting systems and WLED-based solar home lighting systems are considered in this study as various photovoltaic-based domestic rural lighting. The input parameters based on manufacturer/supplier catalogue and market prices are considered for economic evaluation of the different systems and presented in Table 10.

Cost calculations

The cost of various technological alternatives of kerosene-based and renewable electricity-based lighting options is determined. The cost of useful energy (illumination) is used to compare the various light sources. The cost comparison of different options such as kerosene-based lamps, solar lanterns, solar domestic lighting systems, WLED-based solar home lighting systems, biogas-based lighting and biomass gasifier-based systems has been carried out. The cost of useful energy output (illumination) (INR/k-lumen-h) is calculated for all the above options. For simplicity, the daily operation hours in all the systems are considered to be the same. Fuel prices are considered constant in its entire project life and inflation and the salvage value are not considered for simplicity in calculations. All these calculations are made using discount factors of 12%, 10% and 8%. The baseline year of all the costs reported in this study is 2006–2007. Tables 5–8 and 10 provided input parameters for the analysis.

The cost of useful light output (illumination) (INR/k-lumen-h) is calculated based on annualized life cycle cost (ALC) of the systems. The ALC is calculated by considering the annualized capital cost, annual fuel cost and the annualized present value of all the future costs like operation and maintenance cost, component replacement cost etc. The ALC of useful energy for each option is calculated by dividing the annualized life cycle cost of the system with the annual illumination output from the device (Dutt, 1994; Kandpal and Garg,

Table 10
Input parameters for photovoltaic lighting systems.

	Solar lantern	Solar domestic lighting system	WLED-based solar home lighting systems[a]
System cost (INR) (excluding battery)	3800	8000	2800
Battery cost (INR)	700	4000	700
Annual maintenance cost (INR) (% of capital cost)	1	1	1
Life of the system (years)	20	20	20
Life of the battery (years)	5	5	5
Life of the lamp (burning hours)	8000	8000	50,000
Daily operational hours (h)	4	4	4
Numbers of lamp	1	2	2
Each lamp cost (INR)	100	120	325
Each lamp rating (W)	7	9	2.5
Each lamp light output (lumens)	370	600	150
Fuel cost	Nil	Nil	Nil

[a] Surja Bijlee, Solar Energy Lantern ; http://www.suryabijlee.com/.

2003; Rubab and Kandpal, 1997). The expression for calculation of ALC of useful energy can be written as:

$$\mathrm{ALC} = \frac{C_1 \times \mathrm{CRF}(d, n_1) + C_2 \times \mathrm{CRF}(d, n_2) + \ldots + h \times f_C \times f_r + \mathrm{TPV} \times \mathrm{CRF}(d, n)}{L \times \varphi \times h}$$

$$\text{where CRF} = \frac{d \times (1+d)^n}{(1+d)^n - 1} \qquad [1]$$

where C_1, C_2 are the capital costs of the different system components, n_1, n_1 are the life of these components in years, CRF is the cost recovery factor, d is the discount rate, h are annual operation hours, f_c is the unit cost of the fuel, f_r is the specific fuel consumption and n is the total life of the project. TPV is the total present value of the operation and maintenance (O&M) cost. L is the number of lamps in each device and ϕ is the light output (k-lumen) from a single lamp of the device.

In the case of kerosene hurricane lamps and biomass gasifiers, the fuel cost refers to the costs of kerosene and biomass, respectively. However, in the case of solar photovoltaic- and biogas-based lighting systems, the fuel cost considered are zero. (In the former, there is no fuel consumption, while in the latter; the fuel cost is included in the capital cost of the equipment.) The cost of useful energy output (illumination) (INR/k-lumen-h) is calculated by using equation 1 for all the options based on ALC and the results are presented in Fig. 1. Note that kerosene is considered at its open market price rather than the subsidized price available through the Public Distribution System (PDS).

Results and discussions

Technical evaluation

The available options for domestic lighting may be broadly classified into two categories: (i) flame-based and (ii) electricity-based lighting systems. In order to compare various sources of light, luminous efficacy (lumens/W) has been considered as the suitable index (Sinha and Kandpal, 1991). Table 11 shows a comparison between flame-based and electricity-based lighting systems. The efficacies for flame-based lighting systems are much lower than the electricity-based lighting systems.

The luminous efficacy is higher in case of Noorie and Petromax than the traditional kerosene wick lamps (Table 11). In the case of biogas mantle lighting systems, the efficacy is lower than the Noorie or Petromax. However, biogas lamps replace fossil fuels and hence it is better than the traditional kerosene-based systems. The fuel consumption increases during a switchover from kerosene wick lamps to Noorie to Petromax. This is because under typical field condition, a single kerosene wick lamp is replaced by a single Noorie or Petromax, but the light output of the latter is considerably higher than a kerosene wick lamp. It is important to note that, in some cases, improvements in efficiency or efficacy will not necessarily lead to primary energy conservation since lighting level and quality also improves significantly.

Table 11
Comparison between flame-based and electricity-based lighting systems.

	Fuel consumption	Lamp power rating (W)	Light output (lumens)	Efficacy (lumens/W)
Flame-based lighting systems				
Kerosene wick lamp	21.6 (ml/hr)	218	76	0.35
Petromax	80 (ml/hr)	806	1300	1.61
Noorie	50 (ml/hr)	504	1250	2.48
Biogas mantle lighting systems	0.125 (m^3/hr)	799	600	0.75
Electricity-based lighting systems				
Electricity from grid or biogas plants or biomass gasifiers	11(W)	11	900	81.82
Solar lantern	7 (W)	7	370	52.85
Solar domestic lighting system	9 (W)	9	600	66.67
WLED-based solar home lighting systems	2.5 (W)	2.5	150	60.00

Cost comparisons

The cost of useful energy for kerosene wick lamps is highest among all the options (Fig. 1). The cost of useful energy in case of Noorie and Petromax is much lower than that of kerosene wick lamps due to the higher efficacy of these kinds of lamps (Fig. 1). Noorie is a better option considering both technical and economical aspects among all the three kerosene-based lamps. However, this kind of lamp is not widely available in the Indian market and therefore a wide diffusion of this would be necessary if the country continues to depend upon kerosene for illumination (as part of the BAU scenario). The kerosene

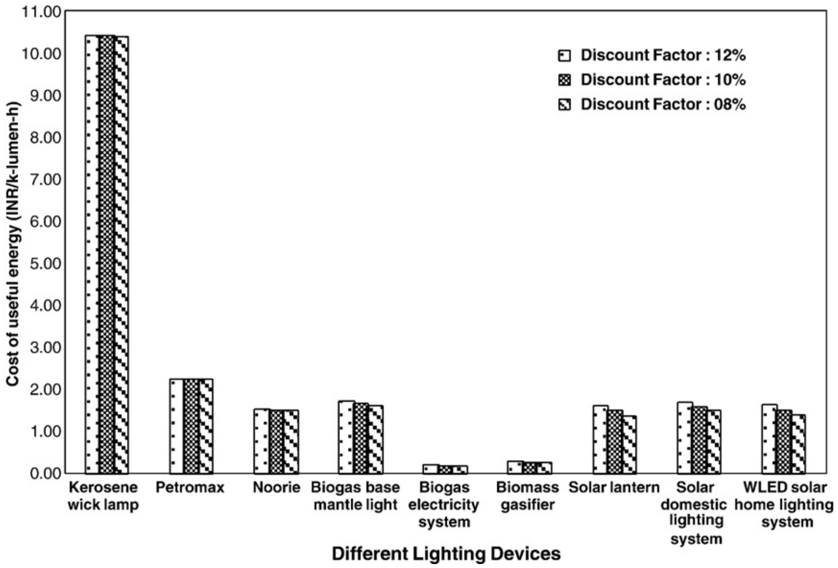

Fig. 1. Cost of useful energy (illumination) for different lighting devices.

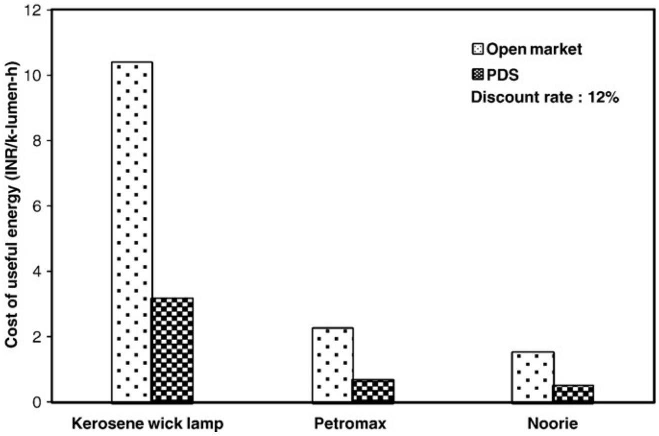

Fig. 2. Cost of useful energy at open market and PDS kerosene for kerosene-based lamps.

price difference between open market and through public distribution system (PDS) in India is high. The price in PDS is highly subsidized by the Indian government. This PDS kerosene is available only to the people below poverty line (BPL). However, the PDS kerosene availability and its distribution mechanism to this BPL population are very poor. The cost of useful energy considering open market price is INR 10.38/k-lumen-h and in PDS price it is INR 3.13/k-lumen-h for kerosene wick lamps (mainly arising from fuel costs, Fig. 2). The cost of useful energy even considering PDS kerosene is still high in kerosene-based lamps in comparison to other options. Biogas-based mantle lighting is widely used throughout the country. The cost of useful energy per hour is INR 1.70/k-lumen-h (Fig. 1). A mini-biogas plant of 1 m^3 size is useful for small family units when exclusively used for lighting purposes. In the case of biogas mantle lighting systems, the cost of useful energy is slightly higher than the Noorie and slightly lower than the Petromax, mainly arising from labor costs. Noorie and biogas mantle lighting systems are better options when choice is limited to flame-based lighting.

Solar photovoltaic-based lighting systems are ideal for domestic lighting applications for rural areas. These systems are useful both for indoor and outdoor domestic lighting. The cost of useful energy for solar lighting systems is lower than kerosene-based lighting systems (Fig. 1). Biogas-based electricity and biomass gasifier system capacity is high and hence the capital cost is also high. Unlike family sized plants using mantle lamps, the larger capacity of biogas electricity systems makes this option applicable to groups of houses supplying animal manure and receiving electricity. The fuel cost for biogas-based electricity systems is considered zero, as the digested biogas slurry is returned to the users (Rajabapaiah et al., 1993). Only the delivery cost of cow dung is considered for the analysis. The biomass gasifier systems are coupled with gas engines and therefore there is no diesel consumption or cost. The cost of illumination using biogas electricity is INR 0.18/k-lumen-h and for biomass gasifier systems is 0.26/k-lumen-h (Fig. 1). The costs of useful light from these two systems are the lowest among all the options considered in this study.

Biomass gasifier and biogas-based electricity system capacity and/or operating hours may be increased by providing electricity to other loads such as drinking water supply, irrigation, flour mills, etc., preferably during other times of the day when lighting energy is not required. Considering the future potential for development and not merely limiting it to providing illumination, this capability becomes important because with every forward step in village development electrical energy needs increase. This capability also paves way for microenterprises.

Decentralized renewable energy systems like biomass gasifier, biogas electricity or solar photovoltaic-based lighting systems are better alternatives to flame-based lighting. Biomass gasifier and biogas electricity are scale sensitive and are usually not economically feasible below a threshold scale. They are suitable for a cluster of households or an entire village, whereas solar photovoltaic-based systems are suitable for single households, since there are no scale economics. The sustainable resource supply and its management as well as successful operation of biomass gasifier and biogas electricity systems require a lot more successful examples. Round the year availability of bright sunlight is required for solar photovoltaic

Table 12
CO_2 emissions in various lighting systems.

Type of system	Fuel consumption	Luminous flux (lumen)	Gross CO_2 emission	Net CO_2 emission	Gross CO_2 emission[e] (g/lumen-h)	Net CO_2 emission[e] (g/lumen-h)
Kerosene-based lighting systems						
Kerosene wick lamp	21.6 (ml/hr)	76	0.055[a] (kg/h)	0.055 (kg/h)	0.728	0.728
Noorie	50 (ml/hr)	1250	0.128 (kg/h)	0.128 (kg/h)	0.102	0.102
Petromax	80 (ml/hr)	1300	0.205 (kg/h)	0.205 (kg/h)	0.158	0.158
Renewable energy -based lighting systems						
Biogas mantle lighting systems	0.125 m^3/hr	600	0.246[b] (kg/h)	Nil	0.409	Nil
Biogas-based electricity	1 m^3 biogas and 80 ml diesel/kWh	81,900[c]	2.185[d] (kg/kWh)	0.00537 (kg/kWh)	0.027	0.00007[e]
Biomass gasifier	1.4 kg wood/kWh	81,900	2.684[f] (kg/kWh)	0.00537 (kg/kWh)	0.033	0.00007
Grid electricity -based lighting systems						
Grid electricity	–	81,900	0.82[g] kg/kWh	0.82 kg/kWh	0.010	0.010

[a] One kilogram of kerosene contains 0.8669 kg of carbon; we considered this fraction of carbon oxidized fully during combustion. Now the CO_2 emission (kg/h) from a kerosene-based lamp will be: $= \text{SFC}\left(\frac{\text{liter}}{\text{hour}}\right) \times \text{Density}\left(\frac{\text{kg}}{\text{liter}}\right) \times \text{Carbon content} \times \left(\frac{44}{12}\right)$. Here, we consider the density of kerosene to be 0.806 kg/l.

[b] We have considered that biogas contains 60% methane and 40% carbon dioxide. Methane is fully oxidized to form CO_2. Now the CO_2 emission (kg/h) from a biogas-based lighting system will be: $= \frac{\text{SFC}\left(\frac{m^3}{\text{hour}}\right) \times \left(\frac{CH_4(\%)}{100} + \frac{CO_2(\%)}{100}\right)) \times 44}{22.4}$.

[c] In case of biogas-based electricity and biomass gasifier-based systems, we considered the fuel consumption per kWh. So the total illumination in each kW will be $= \frac{1000\ (\text{W})}{\text{Each lamp power rating (W)}} \times$ Each lamp lumen output (lumen).

[d] In case of biogas electricity-based lighting systems, we considered that 2 ml lubricating oil is also oxidized during engine operation. We calculate the CO_2 emission from biogas as biogas mantle lighting systems and the CO_2 emission from diesel and lubricant oil as kerosene-based lamps. We consider the density and carbon content of diesel and lubricant oil to be the same. The density is 0.850 kg/l and carbon content is 0.8623.

[e] Gross CO_2 emission considers all CO_2 emitted in combustion. Net CO_2 emission takes into account whether the fuel is renewable or not. Net CO_2 emission from biogas-based electricity and biomass gasifier is due to the oxidation of the lubricant oil only, as otherwise these systems are carbon neutral. Here, we assume that the biomass fuel input to the gasifier is renewable, i.e., does not lead to deforestation.

[f] In case of biomass gasifier-based lighting systems, we also considered that 2 ml lubricating oil is oxidized during engine operation. The wood is represented by $CH_{1.4}O_{0.6}$ and the CO_2 emission from 1 kg of wood is 1.9130 kg.

[g] The grid emission factor (combined margin for 2007–2008) in India is 0.82 tCO_2 /MWh (CEA, 2009).

systems to be successful. Therefore, feasibility and proper installation of all these renewable energy systems depend on availability of site, resources and loads (demand) and therefore needs careful planning.

CO_2 emissions

Kerosene lamps are inefficient and replacing them with electric lamps reduces primary energy consumption. If the energy is fossil-fuel based, then CO_2 emissions are also reduced. In addition to CO_2 emissions, burning of kerosene for lighting produces air borne pollutants that are harmful in the living environment. The CO_2 emissions from kerosene lamps are calculated both as CO_2 emitted per lumen-hour and as kg of CO_2/h to obtain a clear estimate of emissions per unit illumination as well as total emissions. Table 12 represents the annual CO_2 emissions associated with various kinds of devices for lighting systems. The CO_2 emissions in the form of embodied energy from manufacturing of these lighting devices and their accessories are expected to be small and not considered here. CO_2 emission reduction is one way of mitigating climate change. The emission reduction potential would be in choosing one alternative over another, e.g., solar photovoltaic CFL over kerosene wick lamps.

The CO_2 emissions have been found to be 0.73 and 0.10 g/lumen-h for kerosene wick lamp and Noorie, respectively (while net emissions are 0.055 and 0.128 kg CO_2/h). Development requirements will tend to make many households shift to higher illumination and efficiency under current scenario. In such a situation, switch to a higher luminous efficiency device, Noorie and Petromax, by rural households is likely to increase net CO_2 emissions. There are 77 million rural households in India that use kerosene for lighting (Census Report, 2001). Assuming that each of these uses two kerosene wick lamps for an average of 5 h/day, the annual CO_2 emissions are estimated to be 15.46 million tons. In the event all these households switch to Noorie, the CO_2 emissions will rise to 35.97 million tons per year. Table 13 represents the total CO_2 emissions from 77 million households with two lamps each for different lamp technology, fuel and source of electricity.

Electricity generation India is dominated by coal-based power plants, and therefore the emissions factor is relatively high. India's emission factor for electricity generation[2] was 0.82 tCO_2/MWh for 2007–2008 (CEA, 2009). The net CO_2 emission is 0.010 g/lumen-h from grid-based electricity based on 11 W CFL lamps (Table 11). If all 77 million households using kerosene were to switch to two 11 W CFL lamps for 5 h/day, the annual CO_2 emissions would be 2.54 million tons (Table 13).

The CO_2 emissions from renewable energy-based lighting systems have also been estimated. In spite of appreciable gross CO_2 emissions from the biomass gasifier and biogas-based systems, they are carbon neutral. Gross and net CO_2 emissions are estimated for all the different systems. The gross CO_2 emission in the case of biogas mantle lighting is 0.25 kg/h and for biogas-based electricity it is 2.19 kg/kWh. The gross emission per lumen-hour in case of biogas mantle lighting systems is 0.409 g/lumen-h and for biogas-based electricity and for biomass gasifier it is 0.027 g/lumen-h. However, since biogas is a renewable fuel, the net CO_2 emission in case of biogas mantle lighting systems is nil and for biomass gasifier and biogas electricity systems it is 0.0054 kg/kWh. The small net emissions arise due to the oxidation of the lubricating oil used in the engine. Thus, if all the 77 million households were to use two 11 W CFL lamps for 5 h/day supplied by biomass gasifier- or biogas-based electricity, it would release a net emission of 0.0166 million tons CO_2/year (Table 13). On the other hand, CO_2 emissions from solar photovoltaic-based lighting systems are zero.

The CO_2 emissions from grid-based electricity systems are somewhat higher in comparison to renewable energy-based lighting systems but substantially lower compared to kerosene-based lamps. There is thus a great potential for CO_2 emission mitigation by switching over from inefficient kerosene wick lamps either to grid electricity or renewable energy-based lighting systems. CO_2 emission reductions may be monetized through the Clean Development Mechanism of the Kyoto Protocol. Renewable energy-based and grid-based lighting systems could be of interest under the CDM because they directly replace 15.44 million tons of CO_2 emissions (the difference of emissions from kerosene-based wick lamps and biomass or biogas electricity-based systems) and 12.92 million tons of CO_2 emissions (the difference of emissions from kerosene-based wick lamps and grid electricity-based systems) from kerosene-based lighting systems in 77 million households. There is thus a great potential to bundle this opportunity into larger projects such that one can claim CDM benefits.

Table 13
Total CO_2 emissions for different lamp technology, fuel and source of electricity.

Lamp technology and source of electricity	Total CO_2 emissions (million tonnes/year)[a,b]
Kerosene wick lamps	15.46
Kerosene Noorie lamps	35.97
Kerosene Petromax lamps	57.62
Biogas mantle lamps	0
Biomass gasifier or biogas-based electricity and 11 W CFLs	0.0166
Solar photovoltaics and 11 W CFLs	0
Grid electricity and 11 W CFLs	2.54

[a] In the year 2001, 77 million rural households in India used kerosene lamps (Census Report, 2001).

[b] Here, we consider that all 77 million rural households each use two lamps for 5 h daily.

Conclusions

Kerosene lamps like wick lamps, chimney and hurricane lanterns are the most common type of fossil fuel-based lighting in developing countries (especially for rural poor) and the luminous efficacy of these lamps is very low when compared even to inefficient incandescent electricity-based lamps. The light output of these kerosene lamps is low and therefore domestic illumination levels are far below the recommended light levels for any task. A comparison of alternative fuel and electricity-based lighting systems shows that, of the options considered here, the cost of useful illumination is the highest for kerosene wick lamps and is the lowest for biomass gasifier and biogas electricity systems. Electricity-based lighting (from renewable such as solar photovoltaics, biogas and biomass gasifier or grid extension) has potential for providing good quality light compared to flame-based lighting. Switching over from traditional kerosene-based lighting systems to electric systems will lead to significant energy conservation, avoidance of using a fossil fuel such as kerosene, substantial reduction of CO_2 emissions and will also reduce the indoor air pollution while greatly improving the overall quality of life.

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[2] This emission factor, defined in the context of the Clean Development Mechanism, gives equal weight to the average emissions factor of all operating power plants and of recently built power plants.

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